

**An exploration of the effect of resistance training on performance  
and co-ordination during accelerative sprinting.**

Gavin Moir

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## **DECLARATION**

I hereby declare that the composition of this thesis and all the information contained within is entirely my own work.

Gavin Moir    07.12.04



## ABSTRACT

**Purpose:** Accelerative sprint running is an integral component of many sports. Successful performance relies, in part, on muscular strength and so resistance training has been recommended to improve accelerative sprinting. However, an overview of the extant literature investigating changes in accelerative sprint time following a resistance training intervention reveals mixed results. Previous studies have not considered the effect that an increase in muscular strength has on the co-ordination of the sprinting movement. Within the dynamical systems framework, muscular strength can be considered a physical constraint that specifies co-ordination during multi-joint movements. The purpose of this thesis was to investigate the changes in the performance and co-ordination during accelerative sprinting following a period of resistance training, addressing the following research questions:

1. Does a period of resistance training in the absence of concurrent sprint training decrease accelerative sprint time immediately after the training period?
2. Does a period of resistance training in the absence of concurrent sprint training cause a change in the co-ordination of movement during accelerative sprinting immediately after the training period?
3. Can the changes in sprint time and the co-ordination of movement as a result of resistance training be predicted from the magnitude of the gains in strength?

**Method:** Seventeen physically active males participated in a randomised controlled study. An experimental group of 10 men completed an 8-week periodised resistance training intervention, while a control group of 7 men did not train. Pre and post-training measures of 10 m and 20 m sprint time, maximum strength and explosive strength were recorded. The first 3 strides of the 20 m sprint were videoed to provide kinematic and kinetic variables including stride length, stride frequency and vertical and horizontal impulse. Phase-plane diagrams and relative phase (RP) measures of the shoulder, hip, knee and ankle joints indicated changes in co-ordination. **Results:** The resistance training intervention resulted in a significant increase in measures of maximum and explosive strength immediately following the training period, but sprint times were not decreased. Vertical impulse was significantly increased during the first 3 strides of the 20 m sprint, with concomitant decreases in the horizontal impulse following the resistance training intervention. These changes were associated with a significant reduction in stride frequency that contributed to an increase in the sprint times. Despite significant increases in the range of motion about the shoulder and knee joints during the first 3 strides of the sprint and significant increases in the angle of extension about the hip and knee joints at toe-off, the co-ordination between the joints assessed with RP measures was not significantly changed immediately following the training

period. Individual responses to the resistance training intervention were identified with participants who slowed considerably demonstrating substantial increases in extension about the hip and knee joints at touch-down compared to participants whose sprint times changed little. The changes in measures of maximum and explosive strength could significantly predict the change in 20 m sprint time. Moreover, an increase in maximum strength was predicted to cause an increase in 20 m sprint time, whereas an increase in explosive strength was predicted to cause a decrease in sprint time. An increase in maximum strength was predicted to cause an increase in the hip extension at toe-off during the first 3 strides of the sprint. **Discussion:** Although the resistance training increased muscular strength, the pattern of co-ordination that controls the orientation of the ground reaction force with respect to the centre of mass (CoM), which has been identified as a specific constraint associated with the stance period of accelerative sprinting, was not adapted. This constraint, involving the rotation of the CoM forward over the stance leg prior to the proximal-to-distal sequence of joint extensions, allows the generation of long strides and high stride frequencies, increasing sprinting velocity. It was suggested that the decrements in sprint performance were caused by the maintenance of the original inter-joint co-ordination pattern which should be adapted to the increase in the strength of the muscles before an improvement in performance is realised. However, such changes in co-ordination may occur gradually, beyond the duration of the present study. **Conclusions:** The results of the present thesis demonstrate that an 8-week periodised resistance training intervention increased muscular strength but did not improve accelerative sprint performance immediately following the training period. The displacement about the hip and knee joints was increased during the first 3 strides of the 20 m sprint. However, the maintenance of the original inter-joint co-ordination pattern was inappropriate for increasing the horizontal velocity of the CoM at toe-off given the increase in the strength of the extensor muscles, manifest in an increase in vertical impulse. The magnitude of the changes in strength were found to contribute to the changes in both sprint time and the angular displacement about individual joints, highlighting muscular strength as a physical characteristic that influences accelerative sprinting. However, improvements in accelerative sprinting performance cannot be expected until an appropriate co-ordination pattern is adopted that is commensurate with the physical constraints of the motor system.

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## LIST OF ABBREVIATIONS

>	Greater than	GRI	Ground reaction impulse
<	Less than	HA	Hamstrings
$\sqrt{\phantom{x}}$	Square root	Hz	Hertz
$\beta$	Beta coefficient	I	Linear impulse
$\theta$	Angular displacement	ICC	Intraclass correlation coefficient
$\kappa$	Concentration parameter	kg	Kilogram
$\pi$	3.1415927	LSJ	Loaded squat jump
$\rho$	Length of mean vector	m	Metres
$\Sigma$	Sum of	M	Monday
$\sigma$	Standard deviation	ms	Milliseconds
$\hat{\sigma}$	Standard error	MHC	Myosin heavy chain
$\phi$	Phase angle	MPJ	Metatarsal phalangeal joint
$\omega$	Angular velocity	N	Newtons
1-RM	One repetition maximum	N.s	Newton seconds
ACL	Anterior cruciate ligament	<i>P</i>	Probability level ( $\alpha$ )
ANOVA	Analysis of variance	PCSA	Physiological cross-sectional area
$A_m$	Amplitude of sine functions	PP	Peak power output
ARF	Australian rules football	<i>r</i>	Correlation coefficient
BF	Biceps femoris	$R^2$	Coefficient of determination
$B_m$	Amplitude of cosine functions	RF	Rectus femoris
BP	Bench-press	RM	Repetition maximum
CGSS	Clean grip shoulder shrugs	RMSE	Root mean square error
CL	Confidence limits	RoM	Range of motion
CMJ	Countermovement vertical jump	RP	Relative phase
CNS	Central nervous system	s	Seconds
CoG	Centre of gravity	SJ	Static vertical jump
CoM	Body centre of mass	SLDL	Stiff-legged deadlift
CRP	Continuous relative phase	SOL	Soleus
CV	Coefficient of variation	SU	Sit-ups
df	Degrees of freedom	THE	Trunk hyperextensions
EMA	Effective mechanical advantage	TO	Toe-off
EMG	Electromyography	v	Velocity
ES	Effect size	VIF	Variance inflation factor
F	Force	VL	Vastus lateralis
Fr	Friday	W	Watts
GA	Gastrocnemius	We	Wednesday
GRF	Ground reaction force		

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Dedicated to the memory of

Frederick Robinson

1912 – 2004

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# 1. INTRODUCTION

Successful movement demands the co-ordination of many complex biological systems operating on different levels of organisation, e.g. neurons, motor units, muscles. How multi-joint movement arises from the interaction of these different systems is of particular importance to sports coaches. Understanding the nature of the co-ordination of multi-joint movements will guide the development of effective training programmes to optimise sports performance. Similarly, studying movement co-ordination using real-life tasks will provide further insight into the applicability of current motor learning perspectives.

## 1.1 Differing perspectives of multi-joint co-ordination

Typically, the process and structure of multi-joint co-ordination have been considered from a cognitive perspective exemplified in the 'motor programme' (Fitts & Posner, 1967; Keele & Summers, 1976) and 'schema' (Pew, 1974; Schmidt, 1975) theories. Key to these theories is the concept of a set of instructions, or a motor programme, that underlies the organisation and execution of multi-joint movements. Cognitive decisions as to which motor programme to initiate for a given task are based upon the input from perceptual mechanisms, and so the control of co-ordinated, multi-joint movements is centrally based. However, this theoretical position has been questioned because multi-joint movements arise from a system that possesses a number of redundant degrees of freedom and one that is operating under continually changing internal and external conditions (Clark, 1995; Goodman, 1985; Turvey, Fitch & Tuller, 1982; Van Ingen Schenau et al., 1995). Accordingly, an appropriate theory of multi-joint co-ordination requires that the number of elements to be controlled in the changing field of forces (both muscular and non-muscular) be minimised.

A dynamical systems perspective on movement co-ordination suggests that the minimal control criterion is achieved through the formation of co-ordinative structures whereby groups of muscles are constrained to act as single, functional units (Kugler, Kelso & Turvey, 1980). When constrained to function as a co-ordinative structure the individual muscles compensate to preserve the relationship of the collective unit in the face of changing system behaviour, e.g. increased speed of locomotion (Tuller, Fitch & Turvey, 1982). Co-ordinative structures are self-regulating and require minimal input from higher order processes and, as such, their formation would reduce the processing burden of the central nervous system (CNS) when executing multi-joint movements (Goodman, 1985; Kugler et al., 1980).

The formation of co-ordinative structures provides an organisational constraint to the behaviour of the motor system. The concept of a motor system that is bound by constraints is central to the dynamical systems perspective of multi-joint co-ordination. The constraints acting on the motor system have been broadly categorised as those that are found in the organism, the environment and the task (Newell, 1986). These constraints set boundaries for the motor system as well as providing the source of individual differences in movement tasks (Clark, 1995; Newell, 1986). Consequently, movement co-ordination from a dynamical systems perspective is proposed to emerge from the imposed constraints through the physical self-organisation of the underlying biological systems with reference to information available within the environment (Fitch, Tuller & Turvey, 1982; Lee, 1980; Schöner & Kelso, 1988; Turvey, 1990). The process of self-organisation, whereby complex systems comprised of multiple elements spontaneously develop patterns gives rise to the 'organised' co-ordination of movement (Clark, 1995). This contrasts sharply with the central control of movement that is proffered in the cognitive theories, although the central representation of movement is not necessarily absent in a dynamical perspective; rather, movement co-ordination emerges with reference to internal (synaptic) representations (Van Ingen Schenau et al., 1995; Van Wieringen, 1988). Typically, the dynamical systems approach to movement co-ordination has been limited to the study of rhythmical bimanual or single degree of freedom movements (e.g. Carson, 1996; Court et al., 2002; Kelso, 1984) with few studies examining real-life, multi-joint movements.

An important concept from the dynamical systems perspective is that of movement being determined, in part, by the constraints associated with the organism; that is, physical constraints residing in the biological characteristics of the performer. This concept has particular relevance for sports coaches. If the organisation of movements is shaped by physical constraints then the coach can assist the athlete in developing the appropriate co-ordination patterns by manipulating the relevant constraints. Similarly, altering the physical constraints through various training methods will affect the subsequent co-ordination of movement and the performance of the athlete.

## **1.2 Mechanical properties of muscle constraining co-ordination**

An important corollary of this constraints-led approach to movement co-ordination is that the mechanical properties of the muscles represent a constraint limiting the behaviour of the motor system, and so the muscles have a major role in movement co-ordination. The traditional 'top-down' approach to motor control, highlighted in the cognitive theories, where



the outflow of the CNS controls movement and the muscles are regarded as simple force generators, is now giving way to 'bottom-up' models where the muscles actively modulate neural control (Hof, 2003; Zajac & Winters, 1990). It is known that muscle force is modulated by both the velocity of shortening and length changes of the muscle (Fitts, McDonald & Schluter, 1991). Hogan (1990) noted that if muscles are viewed as simple force generators responding to central commands then the CNS would be required to perform complex inverse dynamic computations in order to determine the forces required to execute a given movement. However, these complex calculations are not necessary because of the intrinsic force-length-velocity relationships of muscles. When modelling muscle systems these non-linear properties provide a mechanism for adapting to different internal and external demands (Chapman, 1985; Chapman & Sanderson, 1990; Ettema, 2002; Gerritsen et al., 1998). These mechanical properties of muscles constitute a peripheral feedback system with zero lag time that reduces the effects of perturbations during explosive multi-joint movements (Van Soest & Bobbert, 1993). Therefore, the force-length-velocity relationships ease the motor control task of the CNS. As well as reducing the burden of the CNS, the mechanical properties of muscles also act as constraints that shape movement. Some authors consider the mechanical properties of the muscles to be as important as the nervous system in determining the appropriate pattern of co-ordination for a given task (Bach, Chapman & Calvert, 1983).

What are the consequences for the co-ordination of movement when physical constraints are manipulated? Latash and Anson (1996) have noted that structural or biochemical changes in the CNS, and/or structural changes of the effectors, can lead to different patterns of voluntary movement that reflect the current state of the motor system. It has been proposed that a scale change in the linear dimensions of the motor system is sufficient to produce a sequence of distinguishable patterns of co-ordination for a given movement (Kugler, Kelso & Turvey, 1982). This proposal has empirical support in a longitudinal study examining the developing motor system of growing children assessed during a hopping task where qualitatively distinct patterns of co-ordination were identified as the children's motor system matured (Robertson & Halverson, 1988). This example demonstrates that a change in the magnitude of the system's scale (limb dimensions, mass) can result in a particular co-ordination pattern that is no longer supportive of the given activity. The increases in limb dimensions must be accompanied by changes in the muscular forces that initiate and arrest the motion of the limbs during the movement. Therefore, a new co-ordination pattern emerges that is appropriate for the new parameters of the motor system to achieve the task



goal. However, the original co-ordination pattern may still suffice for the movement if the changes in scale do not exceed a critical value. In a dynamical systems perspective of movement co-ordination, components such as limb length are identified as control parameters that act to constrain the motor system. Control parameters influence the behaviour of the system as revealed in the co-ordination pattern for a given movement (Clark, 1995). The identification of appropriate control parameters that specify the patterns of co-ordination observed during movements has been highlighted as a major task for sport scientists and pedagogists (Handford et al., 1997).

Considering muscular strength as a control parameter, one can envisage co-ordination changes brought about by alterations in the mechanical properties of the muscles moving the limbs. Specifically, a change in the force capabilities of the muscles would affect the torque produced at a particular joint, which would directly affect the acceleration of the limb segments of the joint. How does the movement system accommodate these muscular changes to maintain the effective co-ordination of movements? The results of simulation studies suggest that altering the mechanical properties of the muscles requires a change in the movement co-ordination pattern during multi-joint movements if performance is to be optimised (Bobbert & Van Soest, 1994; Pandey, 1990).

If this scenario is to be investigated using real life, multi-joint movements then it is pertinent to identify the appropriate variables to allow co-ordination changes to be assessed. Newell (1985) proposed that co-ordination for a given movement is revealed in the topological organisation of the relative motion of the constituent elements and that changes in co-ordination can be revealed through the analysis of the topological characteristics of the kinematics associated with the movement. The position and motion of the body segments during a movement can be described by kinematic trajectories. Furthermore, the patterns that define the movement can be represented by these kinematic trajectories, allowing changes in the co-ordination of movement to be revealed in the kinematic patterns associated with the movement.

The magnitude of the change in muscular force is likely to influence the change in the co-ordination pattern for a given movement. As the non-linear qualities of the muscles act as an instant feedback mechanism that compensate for movement errors (Ettema, 2002; Van Soest & Bobbert, 1993), small increases in muscular force may not require a change in the co-ordination of the movement. In this case, the task could be achieved by maintaining the

original co-ordination pattern with the behaviour of certain elements being re-scaled (i.e. an increased range of motion about a joint). However, a large increase in muscular force may render the original co-ordination pattern intractable and so a new pattern of co-ordination emerges that is conjointly appropriate to the motor system's parameters and the movement task. That is, an appropriate co-ordination pattern emerges from the constraints imposed on the motor system.

Understanding the nature of, and the processes associated with transitions between co-ordination patterns is particularly important for coaches as it will allow them to implement appropriate action to optimise athletes' performance. A transition may be preceded by a period of instability, manifested in increased variability of the co-ordination patterns. It has been suggested that such instability represents the motor system re-organising and exploring possible co-ordination patterns to account for structural or dynamic alterations (Riccio, 1993; Schmidt et al., 1992; Schöner, Zanone & Kelso, 1992). Periods of instability have been identified in the locomotory movements of the developing child prior to the formation of the new, stable pattern of co-ordination (Clark & Phillips, 1993). The exploration of different patterns provides perceptual information which guides the selection of an appropriate pattern that satisfies the task constraints (Fitch et al., 1982). During this period of exploration higher-order derivatives of positional information are proposed to provide the necessary information (Cox, 1991). Therefore, changes in higher-order derivatives and higher frequency components of the kinematic trajectories associated with the movement may provide valuable information pertaining to a change in co-ordination.

The influence of muscle mechanical properties on the co-ordination of movement is intuitively appealing and gaining credence in the literature (Carson & Kelso, 2004; Chapman & Sanderson, 1990). However, beyond simulation studies, the effect of alterations in muscle mechanical properties on the subsequent co-ordination of multi-joint movements has received little attention. This area has significant implications for interventions such as resistance training that are aimed at changing muscle properties. This mode of training has been recommended to improve performance in sports that rely on muscular strength and power, such as sprint running (Dintiman, Ward & Tellez, 1998; Donati, 1996; Sheppard, 2003; Young et al., 2001).

### **1.3 Resistance training and sprint running performance**

The literature is replete with investigations examining the cellular and molecular adaptations to resistance training and the concomitant mechanical changes of the muscles. However, details of how these adaptations affect the co-ordination of sporting movements such as sprint running is lacking. An overview of the literature investigating changes in accelerative sprint time following a resistance training intervention reveals mixed results. For example, whilst 3 studies have reported a statistically significant decrease in accelerative sprint time following a resistance training intervention (Gorostiaga et al., 2004; Hennessy & Watson, 1994; Rimmer & Sleivert, 2000), others have reported no significant change (Fry et al. 1991; Gorostiaga et al., 2004; McBride et al., 2002) or even a significant increase (McBride et al., 2002). Where decreases in sprinting times have been reported they have been of a lesser relative magnitude than the increases in the measures of muscular strength.

If sprint performance is to be optimised, it is important to understand why improvements in muscular strength gained through resistance training are not transferred consistently to sprint performance. However, the focus on running time as the performance measure in previous studies does not allow adequate explanations to be posited. The issue of the transfer of muscular adaptations to sporting movements is compounded by the lack of information on the role of muscles during sporting or functional movements (Chapman & Sanderson, 1990; Heckman & Sandercock, 1996; Herzog, 1996). Similarly, researchers tend to neglect the influence of muscle mechanical properties on the movement strategies adopted during sporting activities. Assessing changes in the co-ordination of movement following resistance training would provide valuable information. There is a need for investigations to examine how resistance training affects the co-ordination of the sprinting movement and the impact that any changes may have on subsequent sprint performance.

It is possible that changes in the pattern of co-ordination in accelerative sprinting following a period of resistance training are related to the magnitude of the strength gains relative to the initial strength of the individual. Specifically, large increases in muscular strength may require the formation of a new co-ordination pattern in order to optimise accelerative sprint performance. However, minor increases in muscular strength may be accommodated without changes in the specification of the movement (i.e. through a simple re-scaling of the original co-ordination pattern). Both situations may require a period of exploration by the motor system before performance is optimised. This exploratory period may indicate the readiness

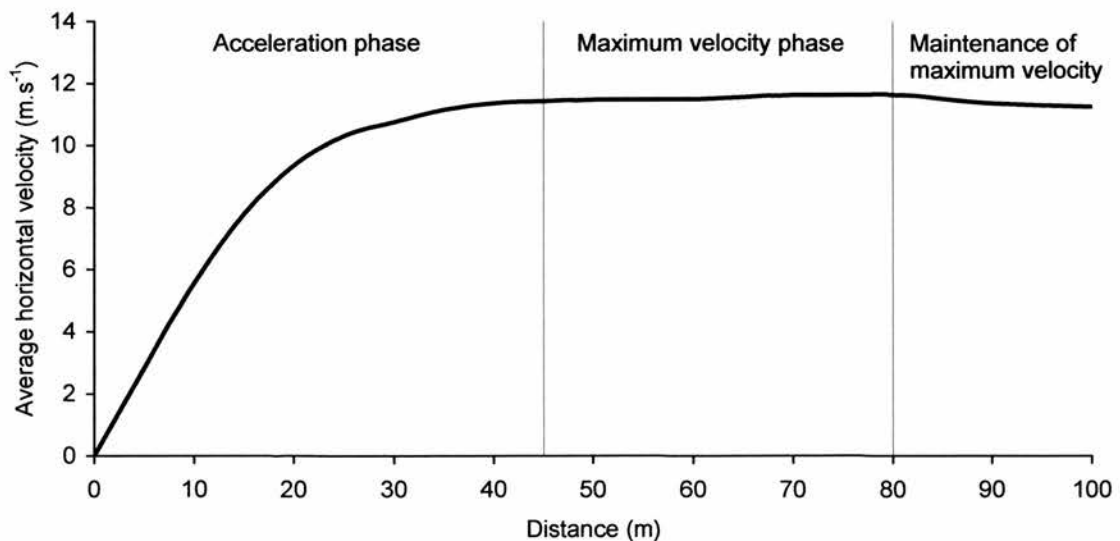
of the motor system to change behaviour and as such could be exploited by the coach (Clark, 1995; Handford et al., 1997).

The purpose of this thesis is to investigate the changes in the performance and co-ordination during accelerative sprinting following a period of resistance training. The findings of this thesis will have implications for the development of training programmes aimed at improving accelerative sprint performance. The present thesis addresses the following research questions:

1. Does a period of resistance training in the absence of concurrent sprint training decrease accelerative sprint time immediately after the training period?
2. Does a period of resistance training in the absence of concurrent sprint training cause a change in the co-ordination of movement during accelerative sprinting immediately after the training period?
3. Can the changes in sprint time and the co-ordination of movement as a result of resistance training be predicted from the magnitude of the gains in strength?

## 2. REVIEW OF LITERATURE

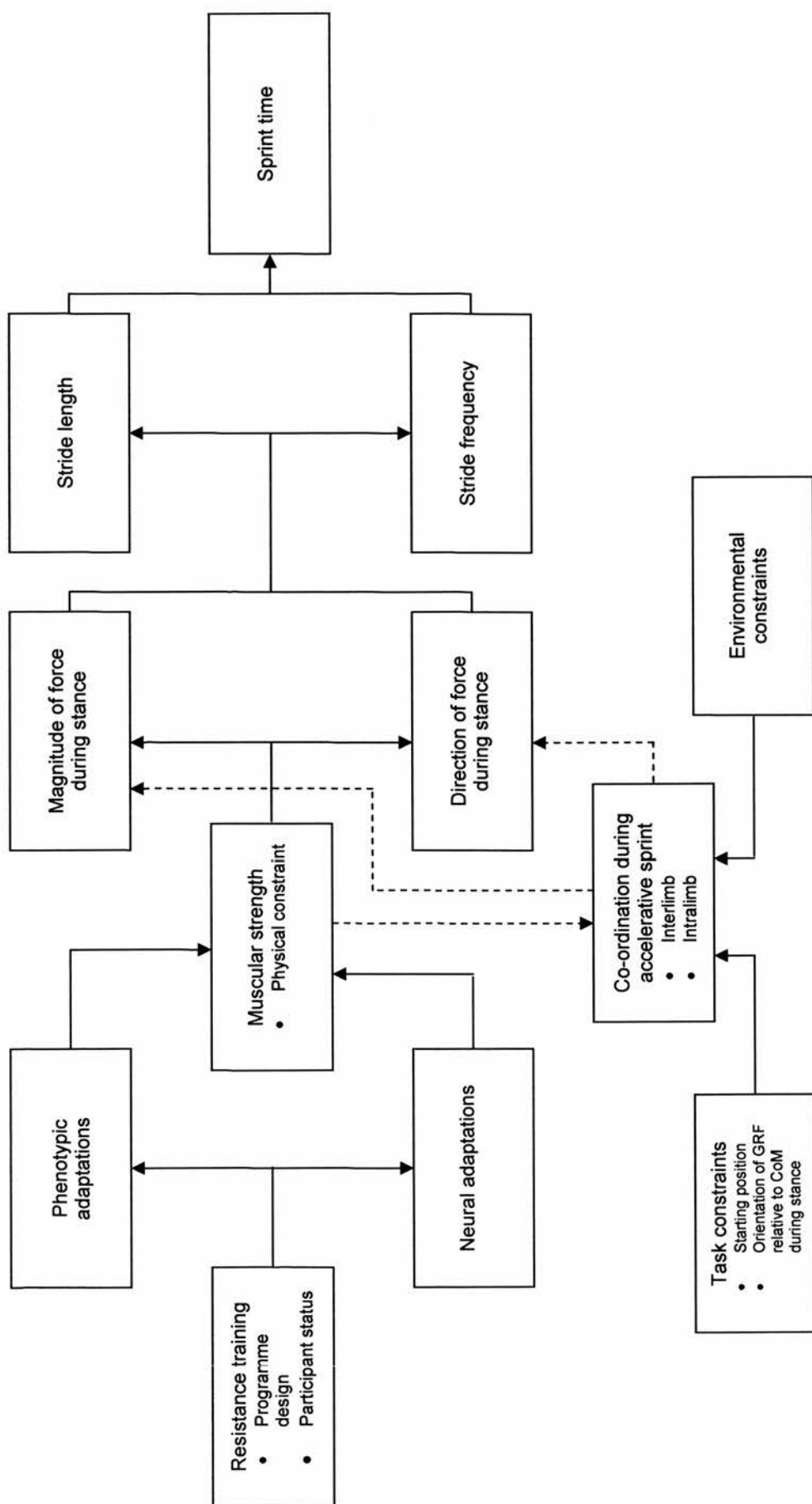
Straight-line sprint running is an integral component of successful performance in many sports. In the past, many coaches and athletes believed that sprinting speed was an innate quality and only modest improvements would result from training (Jarver, 1984). However, it is now generally accepted that relatively large improvements in sprinting speed are possible following training, although there is a lack of consensus on the most effective training methods (cf. Seagrave, 1996; Vittori, 1996). While the effectiveness of different training methods is undoubtedly affected by the training status of the athlete, the consideration of sprint running as a multidimensional skill has important implications. Specifically, sprint running can be regarded as comprising 3 distinct phases: i) initial acceleration, ii) attainment of maximum velocity, and iii) maintenance of maximum velocity (Delecluse et al., 1995a; Murase et al., 1976; Volkov & Lapin, 1979). Figure 2.1 shows the average horizontal velocity of an elite sprinter during a 100 m race and highlights the different phases. This multidimensional structure can be generalised to athletes of differing abilities with adjustments to the duration of each phase. For example, untrained sprinters have been shown to achieve maximum velocity between 10 m and 36 m during a 100 m sprint (Delecluse et al., 1995a), while elite sprinters may not reach maximum velocity until the 80 m point of a 100 m race (Ae, Ito & Suzuki, 1992).



**Figure 2.1** The average horizontal velocity of an elite sprinter during a 100 m race showing the phases of acceleration, attainment of maximum velocity and maintenance of maximum velocity. From: Ae et al. (1992).

The identification of the distinct phases of sprint running has implications for different sports participants. For example, the most important phase for a rugby forward may be the initial acceleration over 10 m, while a rugby back may require development of both the initial acceleration and maximum velocity phases. The disparate phases also have significant implications for training methods used to improve sprint performance. It has been shown that performances during the sprint phases are not perfectly correlated (Baker & Nance, 1999b; Mero, 1988), which suggests that different factors contribute to performance in the distinct phases of sprint running. For example, each phase requires alterations in the functional roles of the active muscles and different neural regulation (Delecluse, 1997; Mero, Komi & Gregor, 1992). The unique requirements associated with the disparate phases of sprinting were revealed in the case study of an elite sprinter over a 4-month period where it was shown that specific training regimes influenced each phase in a different way (Delecluse et al., 1995a).

The focus of this review is the influence of resistance training on the performance and co-ordination during the acceleration phase of straight-line sprint running. The potential effects of a resistance training intervention on accelerative sprinting performance are summarised in Figure 2.2. The dashed lines represent the proposed links between variables that form the rationale for the present thesis. To this end the present review comprises 6 sections. In the first section the mechanical demands of accelerative sprinting are delineated, while in the second section the specific strength requirements are discussed. A brief discussion of the neuromuscular adaptations to resistance training interventions and their importance for accelerative sprinting follows. In the fourth section studies of the effect of resistance training on accelerative sprint performance are critically reviewed. In the fifth section the role of movement co-ordination changes that are likely to mediate the transfer of strength gains to improvements in accelerative sprinting are discussed. While there is no research specific to the effects of strength gains on the co-ordination of movement during sprint running, research of changes in co-ordination during multi-joint movements as a result of adaptations to physical constraints are covered. The chapter concludes with a summary of the main themes in relation to the research questions of the thesis.



**Figure 2.2** A schematic illustration of the potential effects of a resistance training intervention on accelerative sprint time. Note: GRF = ground reaction force; CoM = body centre of mass.



## **2.1 Mechanical demands of accelerative sprinting**

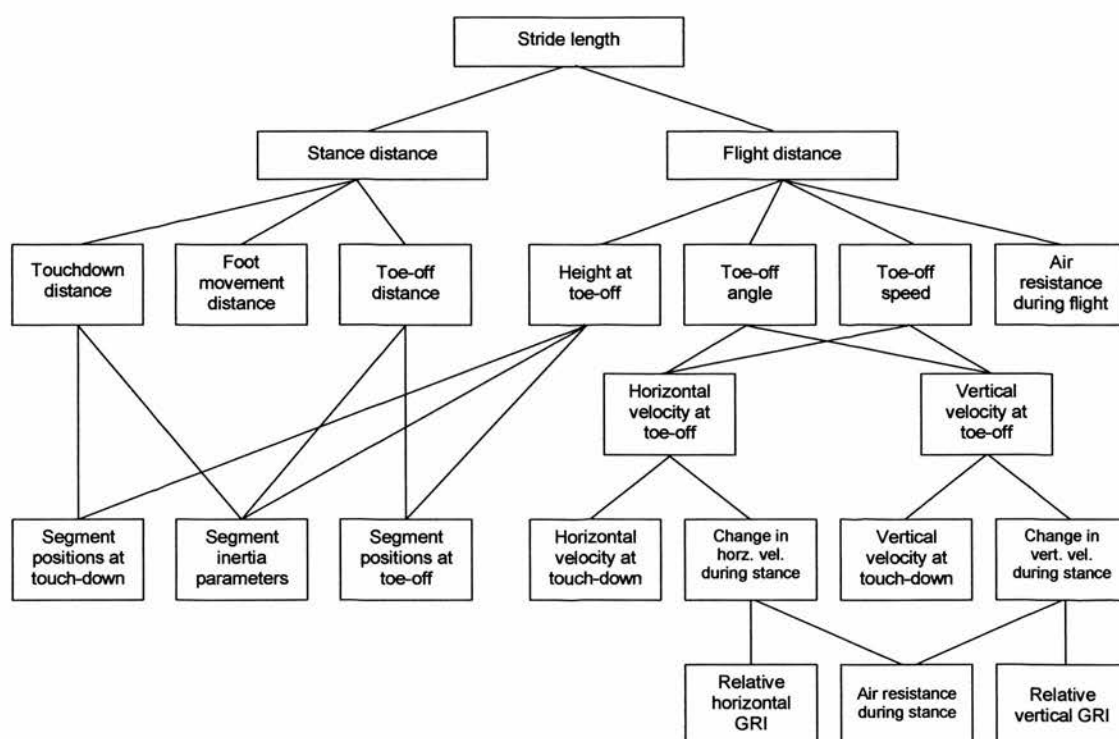
### 2.11 The interaction of stride length and stride frequency

During the acceleration phase of sprint running the athlete must overcome the inertia of the body and propel the centre of mass (CoM) to maximum horizontal velocity. This is achieved by increasing both stride length and stride frequency, with a concomitant decrease in the stance time and an increase in the flight time associated with each stride (Mero et al., 1992). It is the product of stride length and frequency that determines sprint velocity, with elite sprinters producing greater stride lengths and higher stride frequencies than untrained sprinters (Kunz & Kaufmann, 1981). There are conflicting reports in the literature concerning the importance of stride length and stride frequency during accelerative sprinting. For example, field athletes that accelerated faster demonstrated higher stride frequencies than their slower counterparts despite similar stride lengths (Murphy, Lockie & Coutts, 2003). The high stride frequencies were achieved by reducing knee flexion at the end of the stance periods, thus reducing the stance time associated with each stride. However, other researchers found a strong relationship between step length ('step' defining half of a stride cycle) and sprint velocity at the 16 m mark of a sprint ( $r = 0.73$ ) in a heterogeneous group of athletes, while step rate produced only a weak relationship ( $r = -0.14$ ) (Hunter, Marshall & McNair, 2004a). Despite the relationships reported for the group in this study, Hunter et al. (2004a) found that individual sprinters tended to produce their fastest of 3 sprint trials with a high step rate rather than great step lengths. The authors explained their contrasting group and individual findings by suggesting that increasing step rate is a decisive strategy to increase sprinting velocity in the short-term, whereas increasing velocity via greater step lengths, although effective, requires the long-term development of muscular strength.

Hunter et al. (2004a) proposed a number of kinetic and kinematic determinants of stride length and stride frequency (Figures 2.3 & 2.4). For both components the ground reaction impulse (GRI) is a prominent feature, affecting the horizontal and vertical velocity of the CoM at toe-off. Resistance training could be used as a method of increasing the GRI and therefore influencing accelerative sprinting velocity through the interaction of stride length and stride frequency. Differences in the horizontal and vertical velocities at toe-off between sprinters of differing abilities have been shown. In a comparison of male and female sprinters it was shown that male athletes recorded significantly faster times over distances ranging from 5 m to 30 m from a block start (Čoh et al., 2000). Further, horizontal velocity of the CoM at the end of the first and second stance periods was greater in male athletes,



while the vertical velocity was significantly greater in female athletes. The female sprinters produced a greater second stride length on average, although the differences were not significant. Hunter et al. (2004a) identified the vertical velocity of the CoM at toe-off as a source of negative interaction between stride length and stride frequency. Specifically, it was suggested that the long stride lengths and high stride frequencies achieved by elite sprinters was possible only with a technique that involved a high horizontal and a low vertical velocity of the CoM at toe-off. Therefore, while the forces generated during the stance periods of accelerative sprinting are very important for successful performance, the direction of the resultant force is crucial.

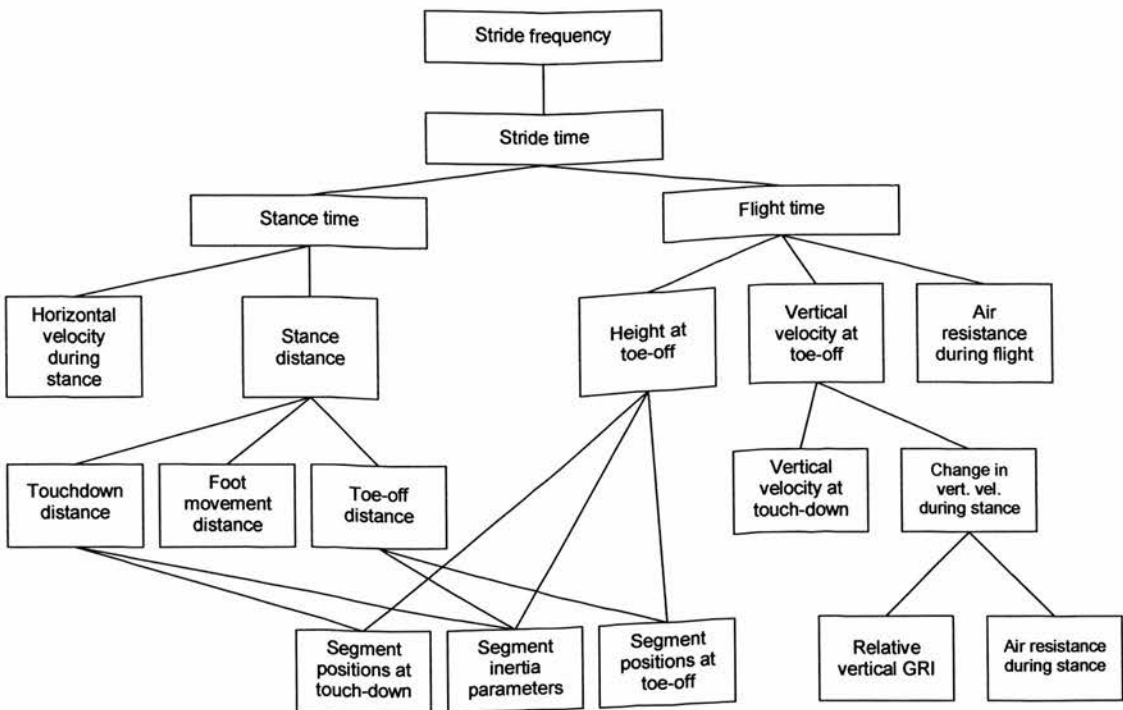


**Figure 2.3** The kinetic and kinematic determinants of stride length. Adapted from: Hunter et al. (2004a). Note: GRI = ground reaction impulse.

## 2.12 The stance period

Mero (1988) reported an average stance duration of  $193 \pm 40$  ms for the first step from a block start in skilled sprinters. Similar stance durations have been reported for field athletes beginning from a standing start (Murphy et al., 2003). The duration of the stance periods are reduced as the athlete accelerates, with durations of 111 ms to 117 ms reported at the 16 m point of a sprint for a heterogeneous group of athletes (Hunter et al., 2004a). The reduction

in the duration of the stance periods as the athlete accelerates means that there is less time to apply the required force to accelerate the CoM. However, altering the force capabilities of the active musculature through a resistance training intervention to allow increased force and impulse despite shorter stance durations would theoretically improve sprint performance.



**Figure 2.4** The kinetic and kinematic determinants of stride frequency. Adapted from: Hunter et al. (2004a). Note: GRI = ground reaction impulse.

Each stance period can be divided into phases of braking and propulsion based on the direction of the ground reaction force (GRF). The braking phase during the first contact from a block start constitutes only 11% of the total stance time, with small horizontal ( $-316 \pm 98$  N) and vertical ( $263 \pm 102$  N) forces associated (Mero, 1988). During the braking phase of the first contact from a block start, reductions in the horizontal velocity of the CoM of between 3% and 11% have been reported, with the higher values recorded for slower athletes (Mero, Luhtanen & Komi, 1983). The majority of the stance periods during the acceleration phase of sprinting comprise a period of propulsion in which the associated forces are much greater than those reported for the braking phase. For example, average peak propulsive forces of  $739 \pm 194$  N and  $788 \pm 96$  N have been reported in the vertical and horizontal directions, respectively, during the first contact from a block start (Mero, 1988). Increases in the horizontal velocity of the CoM of approximately 40% have been reported during the

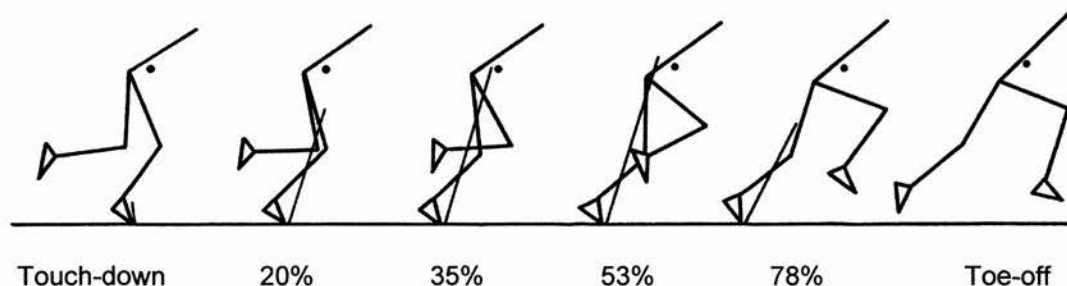
propulsive phase of stance during accelerative sprinting (Mero et al., 1983). Other researchers have found a significant relationship ( $r = -0.64$ ) between the propulsive impulse during the first contact from a standing start and 5 m time in field athletes (Sleivert & Taingahue, 2004). This research emphasises the importance of impulse during the stance periods of accelerative sprinting and implies that increasing impulse during stance by strengthening the active muscles could be an effective means of improving accelerative sprinting.

A limitation of sprinting performance during the acceleration phase is the amount of muscle mass that can be activated during stance and the strength of the extensor muscles of the lower limbs (Van Ingen Schenau, de Koning & de Groot, 1994). In skilled sprinters, large joint power outputs are generated during the push-off from a sprint start, particularly at the hip and ankle joints, with peak extensor power outputs of approximately 1550 W, 620 W and 2180 W reported at the hip, knee and ankle joints, respectively (Jacobs & Van Ingen Schenau, 1992). Greater joint power outputs are generated during the mid-acceleration phase of sprinting, with skilled sprinters producing mean peak extensor power outputs of 3242 W, 1544 W and 3306 W at the hip, knee and ankle joints, respectively (Johnson & Buckley, 2001). A proximal-to-distal sequencing in the joint extensions and power generation of the stance leg has been identified during the early and mid-acceleration phase of sprint running (Jacobs & Van Ingen Schenau, 1992; Johnson & Buckley, 2001). This stereotypical sequencing allows the mono-articular muscles to shorten over a greater range before the end of the stance period and therefore maximise the positive work done (Jacobs & Van Ingen Schenau, 1992). If the joints were to extend simultaneously, the stance foot would lose contact with the ground before the muscles could perform enough work to accelerate the CoM effectively.

The proximal-to-distal sequencing of the muscle activity and joint motions allows power to be transferred between the joints (Jacobs & Van Ingen Schenau, 1992; Jacobs, Bobbert & Van Ingen Schenau, 1996; Johnson & Buckley, 2001). While the mono-articular leg extensor muscles act to accelerate the joints into extension during the stance periods of the initial push-off and mid-acceleration phases, the bi-articular muscles (biceps femoris [BF], rectus femoris [RF] and gastrocnemius [GA]) are responsible for the transfer of power between the joints. For example, the energy liberated at the hip by the action of the hip extensors is transported to the knee by the RF where it is used to accelerate that joint into extension. During the second contact from a block start, Jacobs et al. (1996) reported that power

transferred from the hip by the RF accounted for 31% of the work during knee extension, while power transferred from the knee to the ankle by the GA contributed 28% of the work done by the plantar flexors. Consequently, the large joint power outputs observed at the ankle in the studies mentioned previously may be explained partly by power transferred distally from the large hip muscles via RF and GA.

The proximal-to-distal sequencing of joint extensions also allows the angular accelerations of the joints to be effectively transformed to the translational acceleration of the CoM (Jacobs & Van Ingen Schenau, 1992). However, to achieve this effective transformation there is a specific strategy involving the rotation of the body forward over the stance leg prior to the proximal-to-distal joint extensions (Jacobs & Van Ingen Schenau, 1992). As such, the direction of the GRF changes orientation with respect to the CoM during each stance period (Figure 2.5).



**Figure 2.5** The orientation of the ground reaction force with respect to the centre of mass (•) during the second stance period from a sprint start. The numbers refer to the percentage of the stance period. From: Jacobs & Van Ingen Schenau (1992).

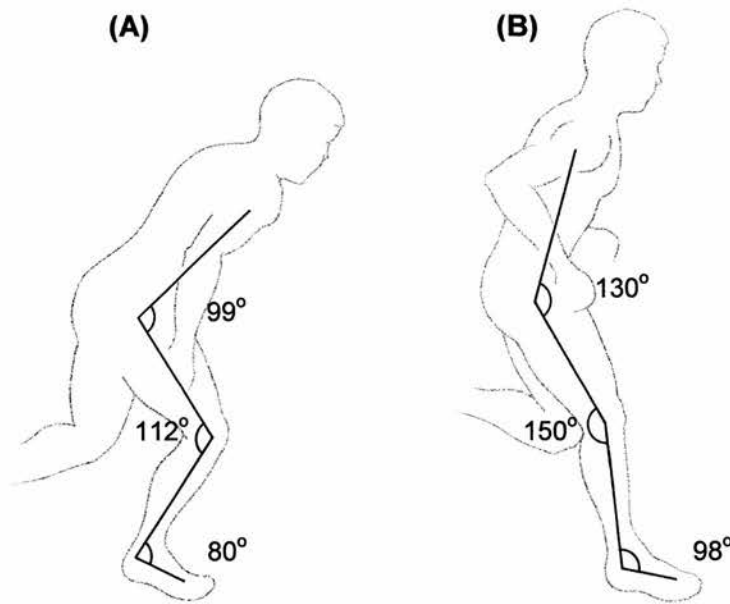
Following touch-down (at 20% of the stance period) the GRF passes anterior to the CoM, decreasing the negative angular momentum of the body. As stance progresses and the body is rotated forward over the stance leg the GRF passes posterior to the CoM causing an increase in negative angular momentum. At this time the stance leg is extended and the CoM is translated horizontally. The change in direction of the GRF, which preserves the angular momentum of the body during the stance periods, is controlled by the reciprocal action of the bi-articular hamstrings and RF muscles and has been identified as a specific constraint associated with accelerative sprinting (Jacobs & Van Ingen Schenau, 1992; Jacobs et al., 1996). It is likely that the specific rotation-extension strategy allows a high horizontal velocity of the CoM at toe-off with a low vertical velocity, producing long strides and high stride frequencies. As such, increasing muscular strength may not improve accelerative

sprint performance if the direction of the GRF is not adequately controlled during stance. Similarly, it is possible that a change in strength could alter the complex sequencing of muscle activations that optimises the flow of power between the joints and the production of force (both magnitude and direction) during the stance periods, impacting on the performance during the acceleration phase of sprinting.

The direction of the GRF with respect to the joints of the stance leg is affected by the geometry of the limb segments (Biewener, 1989). Therefore, the posture adopted during sprinting affects the distance that the GRF acts from the centre of each limb joint. The ratio of the muscle mechanical advantage to the GRF mechanical advantage at each joint, known as the effective mechanical advantage (EMA), represents the leverage with which a given muscle produces force against the ground during stance (Biewener, 1989). When sprinting from a standing start the crouched posture causes a large hip extensor EMA (Card, Weyand & Biewener, 2001). As the athlete accelerates and posture becomes more upright the joints are more extended during each stance period and there is a decline in the mean hip extensor EMA with an increase in the hip flexor moment. This change at the hip causes the whole leg EMA to decrease in the initial steps of the sprint, with the EMA at the knee and ankle joints remaining relatively constant throughout the sprint. The large hip extensor EMA during the first step of a sprint is reflected in the large horizontal component of the GRF reported early in acceleration (Mero, 1988). The crouched posture during acceleration also means that at touch-down, the joints are in a relatively flexed position compared to maximum velocity sprinting (Figure 2.6). This allows the joints to extend over a greater range and therefore the mono-articular extensor muscles can perform greater work before toe-off occurs.

The crouched posture adopted during the acceleration phase also means that the CoM falls little during each stance period (Mero et al., 1992). Consequently, there is limited eccentric muscle activity and little negative work done by the leg musculature. In skilled sprinters it was reported that the amount of negative work done during each stance period of a sprint remained relatively low up to horizontal velocities of approximately  $5 \text{ m}\cdot\text{s}^{-1}$ , following which there was a rapid increase in negative work as running velocity continued to increase (Cavagna, Komarek & Mazzoleni, 1971). These authors concluded that mechanical work is done by the contractile elements of the active leg muscles when accelerating from a sprint start. However, the force produced during each stance period will be limited by the force-velocity relationship of the active musculature (Chapman, 1985), and therefore the acceleration of the CoM will also be limited. Consequently, altering the force-velocity

relationship of the muscles through a resistance training intervention would possibly improve accelerative sprinting performance.



**Figure 2.6** The joint angles of the lower limb at touch-down during the second stance period from a sprint start (A) and sprinting at maximum velocity (B). Data from: Jacobs and Van Ingen Schenau (1992) for (A); Mann et al. (1986) for (B).

Beyond the initial acceleration phase, as running velocity increases and the negative work done by the muscles increases concomitantly, the elastic components of the muscle-tendon complex perform additional work required to sustain higher sprinting velocities up to maximum. It has been reported that the positive work done by the major leg muscles during each stance period decreases as the athlete accelerates to maximum running velocity (Ito, Fuchimoto & Kaneko, 1987), supporting the contention that the acceleration phase requires little negative work to be done by the active musculature. Therefore, the spring-like behaviour of the muscles is unlikely to influence performance during acceleration as it does during maximum velocity sprinting (Kuitunen, Komi & Kyröläinen, 2002).

### 2.13 The flight period

During the flight period the leg is recovered behind and then repositioned in-front of the body in preparation for the next stance period. The importance of this action has been highlighted in a study showing that the swinging thigh is the only segment that produces positive impulse during the braking force associated with the stance period (Mero, Luhtanen



& Komi, 1986). Although the braking forces experienced during the acceleration phase are small compared to those recorded during the maximum velocity phase of sprinting, the action of the recovering leg becomes more important as the athlete progresses through the acceleration phase. Wood (1987) reported that better sprinters generate propulsive forces earlier during stance, and therefore the late stage of leg recovery during the flight period is important for effective force generation. Similarly, inappropriate repositioning of the swinging leg can increase the braking forces experienced during stance (Sprague & Mann, 1983). There is also a transfer of energy from the swinging leg to the contralateral leg late in the flight period (Chapman & Caldwell, 1983). This energy is utilised to recover the contralateral leg following the stance period. Therefore, leg recovery during the flight period is important in sprinting performance, even during acceleration.

#### 2.14 The role of the arms during accelerative sprinting

While the kinematic and kinetic activity of the legs during sprinting has been well described, relatively little is known about the role of the arms, particularly during accelerative sprint running. Minimal muscular contributions at the shoulder and elbow joints have been reported during maximum velocity sprinting (Mann, 1981). Thus, the role of the arms has traditionally been regarded as that of balancing the action of the hips (Hay, 1994; Mann & Herman, 1985). However, Wiemann and Tidow (1995) reported unpublished data demonstrating that changing the arm action during sprinting (sprinting with both arms fixed to the trunk and sprinting with elbows fully extended) can increase sprint time by between 3% and 10%. It has also been demonstrated that during sub-maximal running the action of the arms contributes to the vertical momentum of the body during late stance and this contribution increases with running velocity (Hinrichs, Cavanagh & Williams, 1987). It has been speculated that during the acceleration phase of sprinting when the body has a pronounced forward lean, the vertical lift of the arms could contribute to the forward propulsion of the body (Hinrichs et al., 1987).

It is possible that the action of the arms during the stance periods of sprint running may augment the torques generated at the hip and knee joints and therefore influence the magnitude of the GRF prior to toe-off. It was shown in a recent investigation of vertical jump performance that the torque at the hip and knee joints was increased during propulsion as a result of swinging the arms prior to take-off (Feltner, Frascchetti & Crisp, 1999). The arm action was proposed to slow the rate of hip and knee extension during the early phase of propulsion, allowing the extensor muscles to shorten at a more effective point on the force-

velocity relationship when they are in an advantageous position to generate force. The vertical velocity of the CoM and the peak vertical GRF were increased during vertical jumps as a result of the swinging arm action (Feltner et al., 1999; Harman et al., 1990). It is possible that the arms perform a similar role during the stance periods of sprint running. However, little consideration is given to the action of the arms when developing resistance training programmes for sprint running.

#### 2.15 The effect of starting position on accelerative sprinting

In a stationary start, the position adopted has a significant effect on sprinting performance. For example, the distance between the hands and the front foot during a start from starting blocks and the angle of the foot plates of the blocks affect the force produced and the horizontal velocity during the initial push-off (Guissard, Duchateau & Hainaut, 1992; Schot & Knutzen, 1992). Similar differences have been reported between a standing start preceded by a step backwards and a standing start from a stationary position (Kraan et al., 2001). The step backward allows the CoM to be projected in-front of the stance leg much quicker, and a forward GRF is produced without the time taken to rotate the body forward over the stance leg (Kistemaker & Faber, 2002). Henry (1952) noted that differences in starting block set-up resulted in differences in times over 10 and 50 yards. Although these differences were only reported for a start from starting blocks it seems reasonable to assume that sprint performance can be influenced by the posture adopted during a standing start.

#### 2.16 Summary

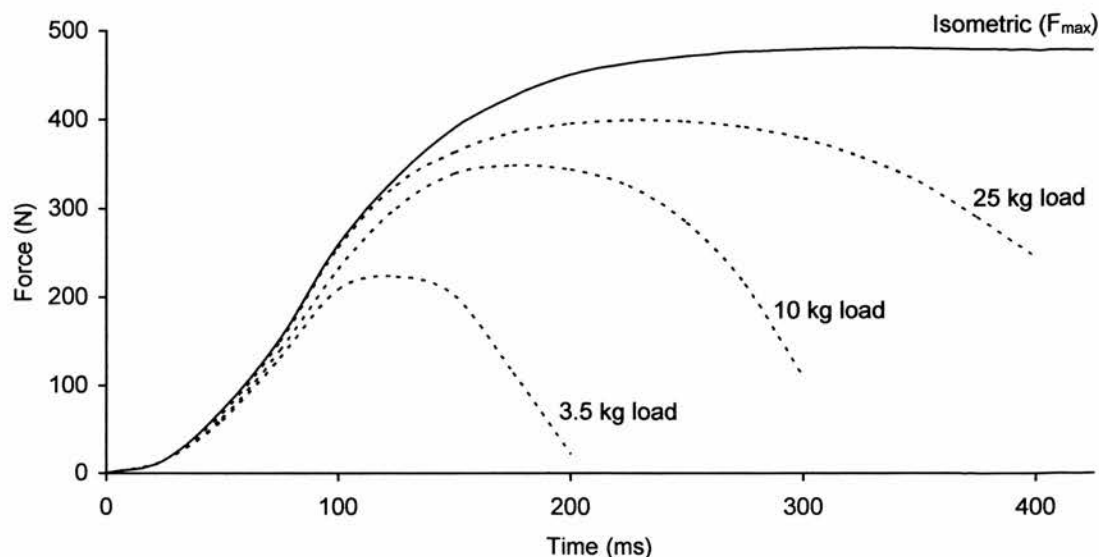
Sprinting velocity depends on the interaction of stride length and stride frequency. Which of these components is more important for accelerative sprinting is unclear, but both have many kinetic and kinematic determinants. Of the determinants that can be influenced by resistance training, the GRI affects both the horizontal and vertical velocity of the CoM at toe-off. Increasing the horizontal velocity of the CoM at toe-off is an effective strategy to improve acceleration. However, the vertical velocity of the CoM at toe-off increases the flight time of each stride which decreases stride frequency, and so it has been identified as a source of negative interaction between stride length and stride frequency. The large propulsive forces produced during the stance periods are the result of the concentric action of the mono-articular leg extensors, with power being transferred by the bi-articular muscles. The bi-articular muscles are crucial in controlling the orientation of the GRF with respect to the CoM, which has been identified as a specific constraint during the stance periods of accelerative sprinting. It is possible that a change in strength could alter the complex



sequencing of muscle activations that optimises the flow of power between the joints and the production of force (both magnitude and direction) during the stance periods, impacting on the performance during the acceleration phase of sprinting. Although propulsive force is applied through the ground leg during stance, the action of the swinging leg during the flight period and the action of the arms are also likely to influence the performance. Similarly, the starting position has a significant effect on performance during the acceleration phase of sprinting.

## **2.2 Strength requirements of accelerative sprinting**

Insight into the strength requirements of accelerative sprint running can be gained by assessing the relationships between sprint performance and measures of strength. Strength is the ability to produce force (or torque) under specific conditions defined by posture, muscle action (concentric, eccentric, isometric, isokinetic, stretch-shortening cycle) and movement velocity (Harman, 1993). Within this definition there exist a number of specific indices of strength. Maximum strength is the ability of a particular group of muscles to produce a maximum voluntary contraction against an external load (Siff, 2000). Maximum strength is usually assessed as the peak force or torque achieved in a given test, or the maximum weight lifted in a particular movement (e.g. back squat). Relative maximum strength is the maximum strength value normalised to body mass (Jaric, 2002). Tests of maximum strength are usually unrestricted by the duration of the period of force application. However, during sporting actions such as sprint running the application of force occurs rapidly (e.g. a stance period of 193 ms) such that the production of maximum force is not possible (Viitasalo, Häkkinen & Komi, 1981). Many authors have suggested that measurements of maximum force are not indicative of the contractile properties of a muscle, and that the force capabilities of muscles should be examined under conditions of varying time, speed and acceleration (Green, 1992; Komi, 1984; Tidow, 1990) (Figure 2.7). Accordingly, explosive strength is defined as the ability to produce large force or torque values in a limited period of time with high rates of force development (Schmidtbleicher, 1992). The expression of explosive strength is associated with high movement velocities. Assessments of explosive strength include vertical jump performance under different load conditions with the measurement of jump height or force-time variables associated with the movement (Tidow, 1990; Young, 1995). Despite these different expressions of strength, within groups of trained sprinters the faster athletes can be distinguished from their slower counterparts on measures of both maximum and explosive strength (Meckel et al., 1995; Mero et al., 1981).



**Figure 2.7** Force-time curves from isometric and concentric actions against different loads. From: Schmidbleicher (1992).

The mechanical demands of accelerative sprinting require the body to be propelled primarily by the leg extensors. This demand is reflected in the strong relationships demonstrated between relative measures of maximum isometric and isokinetic torque of the knee extensors and accelerative sprint performance in sprint athletes (Dowson et al., 1998; Mero et al., 1983) (Table 2.1). However, the strength of the relationship between maximum knee extension torque and accelerative sprint performance is reduced when absolute torque values are used (Dowson et al., 1998). A similar pattern is revealed when the power output during vertical jumps is analysed. For example, Baker and Nance (1999b) found a stronger relationship between accelerative sprint time and power relative to body mass ( $r = -0.61$ ) than between sprint time and absolute power output ( $r = -0.08$ ). The influence of body mass in these relationships probably arises from the reliance of acceleration on the interaction of force and mass (re-writing Newton's second law,  $\text{acceleration} = \text{force}/\text{mass}$ ).

The requirement for the application of force at high velocities during accelerative sprinting has been shown by the strengthening of the relationship between sprint performance and relative isokinetic knee extension torque as the velocity of knee extension is increased (Dowson et al., 1998). However, when the acceleration phase is short there is a greater reliance upon high force production as opposed to high movement velocity. For example, Sleivert and Taingahue (2004) reported that peak force during a one repetition maximum (1-

RM) squat was more substantially related to 5 m time ( $r = -0.59$ ) than the vertical velocity of the barbell ( $r = -0.40$ ).

**Table 2.1** Relationships between measures of absolute and relative maximum strength and accelerative sprinting.

Authors	Sample	Sprint measure	Strength measure	$r$
Cometti et al. (2001)	Soccer players	10 m time	Absolute: Various measures	-0.06 to 0.13†
Dowson et al. (1998)	Sprinters, rugby players	15 m time	Relative: Knee extension	-0.41 to -0.58
Kukolj et al. (1999)	Students	0.5 – 15 m time	Relative: Knee extension	0.22
Mero et al. (1983)	Sprinters	2.5 m velocity	Relative: Knee extension	0.60

Note: † Personal communication N.A. Maffiuletti, 19.02.03.

As shown in Table 2.2 measures of explosive strength are strongly related to accelerative sprint performance (Berthion et al., 2001; Bret et al., 2002; Hennessy & Kilty, 2001; Mero et al., 1983; Young, Hawken & McDonald, 1996; Young, McLean & Ardagna, 1995). There appears to be an effect of athletic status that influences the relationship between accelerative sprint performance and strength indices, particularly measures of maximum strength. For example, trained sprinters demonstrate strong relationships between sprint performance and both relative maximum and explosive strength indices (Mero et al., 1983). However, in research using untrained sprinters, weak relationships have been demonstrated between accelerative sprint performance and maximum leg strength assessed in both absolute (Cometti et al., 2001) and relative measures (Kukolj et al., 1999). Fahey (2001) reported data examining the relationship between 10 m sprint time and isokinetic leg strength in both trained sprinters and non-sprinters. A stronger relationship was revealed in the sprint athletes ( $r = -0.85$ ) than the non-sprint athletes ( $r = -0.72$ ). Moreover, the regression line for the sprint group was much steeper than that of the non-sprint athletes. In effect, it appears that strength may have a greater influence on accelerative sprint performance in trained sprinters than their untrained counterparts.

**Table 2.2** Relationships between measures of explosive strength and accelerative sprinting

Authors	Sample	Sprint measure	Strength measure	<i>r</i>
Berthion et al. (2001)	Students	Acceleration over 2 s	CMJ height	0.73
Bret et al. (2002)	Sprinters	Velocity at 30 m	CMJ height	0.66
Hennessy & Kilty (2001)	Sprinters	30 m time	CMJ height	-0.60
Mero et al. (1983)	Sprinters	Velocity over 2.5 m	CMJ height	0.70
Young et al. (1996)	ARF players	20 m time	CMJ height	-0.66
Young et al. (1995)	Sprinters	2.5 m time	Force during LSJ‡	-0.86

Note: CMJ = countermovement vertical jump; ARF = Australian rules football; LSJ = loaded static vertical jump; ‡ Peak force relative to body mass.

### 2.21 Summary

Muscular strength is an important factor contributing to accelerative sprinting. This is reflected in the relationships between sprint performance and measures of strength, particularly maximum and explosive strength relative to body mass. Early during the acceleration phase of sprinting there is a need for high force production as opposed to high movement velocity in order to overcome the inertia of the body mass. As the acceleration distance increases there is a greater requirement to produce force during high movement velocities. It is possible that strength has a relatively greater effect on the starting velocity in accomplished sprinters compared to untrained sprinters, although the reasons for this are unclear.

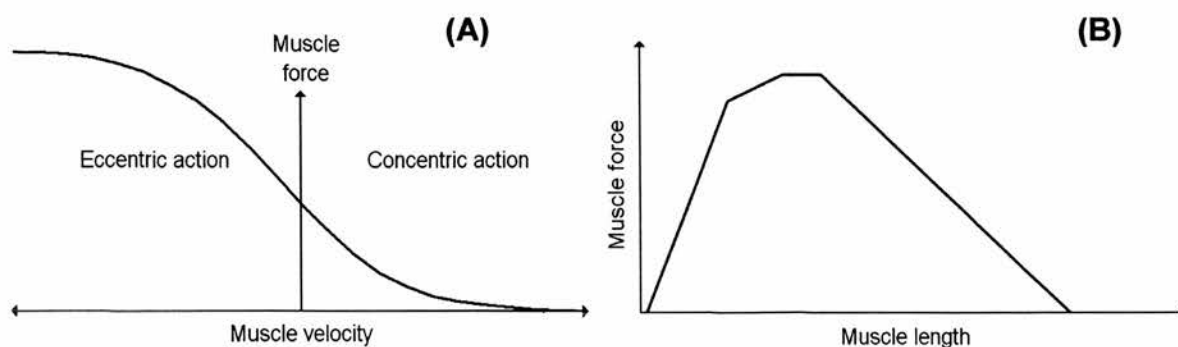
From the preceding review it is clear to see why resistance training has been implicated as an intervention to improve accelerative sprinting performance. However, the cross-sectional nature of the preceding studies does not allow the causal influences of resistance training on sprint running performance to be elucidated. Based on the preceding analysis of accelerative sprint running it appears that a resistance training regime could be effective in improving accelerative sprinting performance by increasing muscular strength.

### **2.3 The effect of resistance training on muscular strength**

Resistance training regimes have been shown to increase measures of muscular strength, power and local muscular endurance. However, the improvements gained are dependent

upon the initial training status of the participant, the exercises used, and the specific design of the programme (Kraemer et al., 2002). There is a hierarchical relationship between maximal muscular strength and power, with strength being the basic quality that influences power performance (Baker & Nance, 1999a; Moss et al., 1997; Schmidtbleicher, 1992). During movements under high load conditions maximum strength appears to have its greatest influence on power at the beginning of the movement to overcome inertia (Häkkinen & Komi, 1985). However, a strong relationship between maximum strength and power outputs during unloaded movements or those performed with very low loads has also been demonstrated ( $r = 0.73$ ) (Moss et al., 1997).

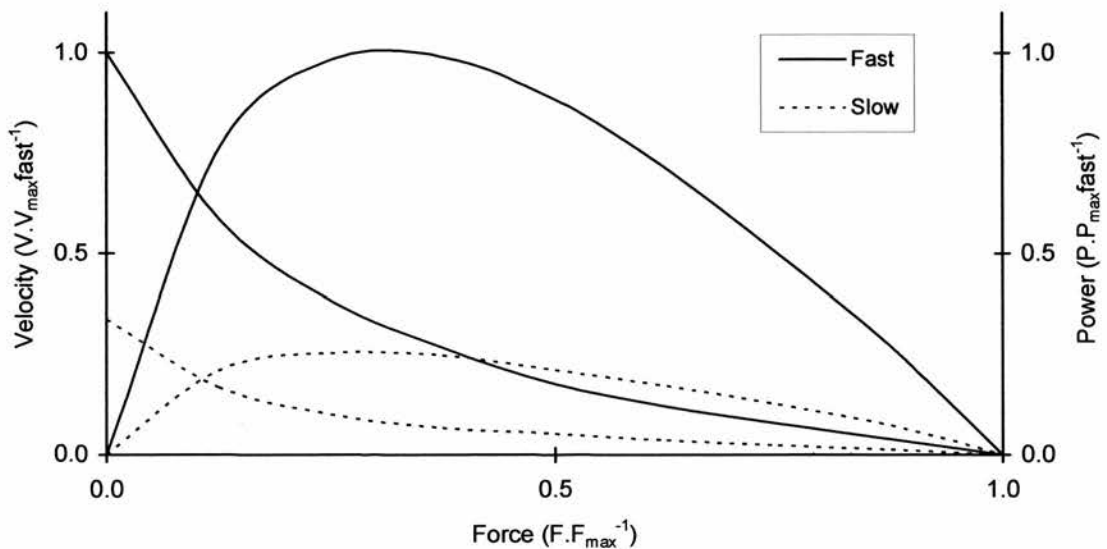
The expression of muscular force is determined by the rates of muscle activation and relaxation and the force-velocity and force-length relationships (Figure 2.8) (Caiozzo, 2002; Herzog, 2000). These properties are dependent upon the interaction of numerous factors including fibre characteristics (type, size and length), muscle architecture (pennation angle, fibre to muscle length ratio), number of cross-bridges in parallel, force per cross-bridge and innervation characteristics (Enoka, 1990; Fitts et al., 1991). The neuromuscular system displays great plasticity under altered environmental demands such as the changes in recruitment pattern and loading associated with a resistance training intervention. The physiological mechanisms activated by the stimulus of resistance training cause a variety of cellular and molecular adaptations within the neuromuscular system (Booth & Thomason, 1991; Deschenes & Kraemer, 2002). These adaptations can be broadly categorised into changes in phenotypic and neural factors, which will be discussed initially. Following this there will be a brief discussion of the influence of programme design, the participant's training status and exercise specificity on the gains in strength.



**Figure 2.8** Schematics of the idealised force-velocity (A) and force-length (B) curves for muscle. Adapted from: Herzog (2000).

### 2.31 Phenotypic adaptations to resistance training

Muscle fibres are capable of phenotypic transitions to adjust their sarcomeric proteins in response to altered use (Baldwin & Haddad, 2001; Pette, 2002). For example, long-term (20-weeks) resistance training causes type IIB to IIA fibre-type conversions (Staron et al., 1991), while 10-weeks of resistance training has been shown to cause a decrease in myosin heavy chain (MHC) type I and type IIb isoforms with a corresponding increase in type IIa (Kadi & Thornell, 1999). The expression of MHC isoforms has significant implications for the force-velocity relationship of an individual muscle. Muscle fibres expressing fast MHC isoforms can produce greater force under increased shortening velocities and have a greater rate of force development than those fibres expressing slower MHC isoforms (Fitts et al., 1991; Schiaffino & Reggiani, 1996). Similarly, the power output of fast muscle fibres is greater than that of slower fibres (Faulkner, Claflin & McCully, 1986) (Figure 2.9).



**Figure 2.9** Velocity of shortening and power output as a function of force for fast and slow muscle fibres of humans. Velocities and power outputs are normalised by maximum velocity of shortening and maximum power outputs of the fast fibres. From: Faulkner et al. (1986).

These muscular properties would benefit sprint performance where there is a need for force production at high joint angular velocities. Indeed, faster sprinters have been shown to have a higher percentage of fast muscle fibres (type IIA) in the vastus lateralis (VL) than their slower counterparts (Mero et al., 1981). The link between muscle fibre characteristics and sprint performance under the influence of resistance training has been identified. A 3-month period of combined sprint and resistance training caused a decrease in muscle fibres



containing only MHC I isoforms in the VL of trained sprinters, with a concomitant increase in those fibres containing only MHC IIa isoforms (Andersen, Klitgaard & Saltin, 1994). These athletes showed an improvement in sprint performance during the same period, although it is difficult to delineate the role of resistance training on the changes in the fibre characteristics and the changes in sprint performance.

Short-term phenotypic adaptations also occur in response to resistance training with an increase in myofibrillar protein synthesis reported within 2 weeks of beginning a regime (Hasten et al., 2000; Yarasheski, Zachwieja & Bier, 1993). Significant decreases in MHC IIb and an increase in type IIa isoforms have been reported within 4 weeks of starting a resistance training regime (Staron et al., 1994). Indeed, an up-regulation of MHC gene expression has been reported following a single resistance training session (Willoughby & Nelson, 2002). Although it is not known to what extent this remodelling of the muscle fibres may contribute to the expression of muscular strength, these alterations in muscle 'quality' during the early phase of a resistance training programme should be considered (Kraemer, Fleck & Evans, 1996). For example, a shift from MHC IIb to IIa isoform content could increase strength because the lower recruitment threshold associated with the type IIa motor units (Henneman, Somjen & Carpenter, 1965) may increase the ability of these fibres to be recruited during forceful muscle contractions.

An increase in the cross-sectional area of all muscle fibre types has been reported after 20-weeks of resistance training (Staron et al., 1991). Extreme muscle hypertrophy occurs as a result of long-term exposure to a resistance training stimulus (MacDougall et al., 1982). Although fibre hypertrophy and the associated increase in the physiological cross-sectional area of the muscle would be expected to increase the force generated by the muscle, extreme hypertrophy would not necessarily be beneficial for sprinting due to the associated increase in body mass. However, the degree of hypertrophy is dependent upon the resistance training programme and the training status of the individual. For example, limited muscle fibre hypertrophy has been reported in resistance-trained athletes (Olympic weight-lifters) over the course of a 2-year training period, despite increases in strength during this period (Häkkinen et al., 1988). This suggests that there is an upper limit on fibre cross-sectional area and that other factors influence strength development in well-trained athletes.



### 2.32 Neural adaptations to resistance training

Muscular force is dependent upon the ability of the nervous system to activate the muscles. Neural adaptations that follow a resistance training intervention are widely distributed throughout the nervous system. For example, adaptations in the motor commands, the distribution of activity among the active muscles, the motor unit activity within individual muscles and facilitated sensory feedback have been reported as a result of resistance training (Duchateau & Enoka, 2002; Semmler & Enoka, 2000). The neural factors that appear to have the greatest benefit for sprint running performance are an increased frequency or degree of muscle innervation and a change in the temporal sequencing of muscle activations (Ross, Leveritt & Riek, 2001).

The early strength gains during a resistance training programme are associated with increased muscle activation (electromyography [EMG]) in the absence of muscle fibre hypertrophy (Aagaard et al., 2000; Akima et al., 1999; Ploutz et al., 1994). The increase in EMG signals indicates changes in motor unit recruitment, firing frequency and the synchronisation of motor unit action potentials (Aagaard, 2003). An increase in the electrically invoked force, which is indicative of increased muscle activation, has also been reported following a period of resistance training (Duchateau & Hainaut, 1984). However, the increased muscle activation appears to be specific to the joint angle (Thépaut-Mathieu, Van Hoecke & Maton, 1988) and the movement used in the resistance training exercises (Häkkinen & Komi, 1983).

Explosive resistance training where movements are performed as quickly as possible regardless of the load has resulted in an increase in the rate of onset of motor unit activation, as revealed by surface EMG (Häkkinen, Komi & Alén, 1985). Similarly, an increase in motor unit torque and the initial rate at which the motor units are discharged has been reported following explosive resistance training (Van Csem, Duchateau & Hainaut, 1998). An increase in the rate of motor unit activation would be associated with an increased rate of force development which would be beneficial for sprinting. The amplitude of the evoked V-wave response has been shown to increase following a period of resistance training (Aagaard et al., 2002). The evoked V-wave reflects the level of efferent neural drive from  $\alpha$ -motoneurons during maximal muscle activation (Upton, McComas & Sica, 1971) and so changes in the V-wave can result from changes in motoneuron firing frequency and/or motoneuron recruitment. Increases in either of these would benefit sprint athletes. Indeed, increased V-wave responses have been observed in sprint athletes compared with untrained

participants (Upton & Radford, 1976). Resistance training has also been shown to cause an increase in the gain of the corticospinal pathway such that a lower level of cortical input to the spinal motoneurons is required to generate a particular level of muscle activation (Carroll, Riek & Carson, 2002). A consequence of this adaptation is that there is an enhancement in the stability of movements similar to those used in the resistance training intervention (Carroll et al., 2001a). This point will be elaborated in Section 2.5.

During normal movements, the interaction between the individual muscles that cross joints is important for the required generation of force (Semmler & Enoka, 2000). This would take the form of the most efficient activation of all the muscles involved in the movement. Resistance training using leg extensions has been shown to decrease the co-activation of the hamstrings during maximum leg extension exercise (Häkkinen et al., 2000). Significant decreases in agonist-antagonist co-activation have been reported after only 2-weeks of isometric resistance training (Carolan & Cafarelli, 1992). The decrease in co-activation was accompanied by a significant increase in strength, with no change in the activation of the agonist muscles. Such adaptations have been implicated in the role of learning associated with resistance training (Rutherford & Jones, 1986).

It is believed that the increases in strength observed early in a resistance training programme (3 to 5-weeks) are the result of neural adaptations (Moritani & De Vries, 1979; Sale, 1992). While neural adaptations may confer the most dramatic influence on the strength adaptations early in a resistance training programme, phenotypic adaptations should not be overlooked. Similarly, the stimulus of resistance training activates a variety of other processes, such as the response of the endocrine system, which support the phenotypic and neural adaptations of the neuromuscular system to resistance training (Kraemer, 1992). It is the interaction of these complex processes and the co-ordination between the muscles involved in a particular movement that is revealed in the expressions of muscular strength following a resistance training intervention.

### 2.33 Programme variables that mediate adaptations to resistance training

The physiological mechanisms activated by a resistance training intervention, and the subsequent phenotypic and neural adaptations depend upon the design of the resistance training programme. In combination with the duration of the training programme, the acute programme variables that have greatest impact on the development of strength are the choice of exercises, the number of repetitions and sets, the rest periods between exercises and sets,

and the intensity or the resistance used during each exercise (Kraemer et al., 2002; Kraemer et al., 1996). Periodised resistance training programmes, where the variables of volume and intensity are systematically varied to optimise the training stimulus, have been shown to be more effective than traditional programmes in eliciting strength gains (Kraemer, 1997; Kraemer et al., 2000; Willoughby, 1991). The general methods of periodisation involve moving from high repetitions with low loads to low repetitions with high loads, and a progression from general to specific exercises (Kraemer et al., 2002).

The loads used during a resistance training regime produce specific adaptations. For example, an intervention of heavy resistance training produces large increases in maximum force (Häkkinen, Alén & Komi, 1985), while training with lighter resistances moved quickly produces greater gains in force-time characteristics such as the rate of force development (Häkkinen, Komi & Alén, 1985). Given the strong relationship that exists between maximum strength and power output (Cronin, McNair & Marshall, 2000; Moss et al., 1997), it has been suggested that in order to provide a greater stimulus for the neuromuscular system to adapt, a combination of high force and high velocity resistance training should be used (Cronin, McNair & Marshall, 2002; Newton & Kraemer, 1994; Stone, 1993). It is proposed that this will allow a greater transfer of training effect to athletic skills that rely on strength and speed (Baker, 1996). The rationale behind combined regime training is based upon providing a periodised and varied resistance training programme whereby strength development is the purpose early in the intervention, with the emphasis later switching to power and speed development. Research has shown that this combined approach is successful in improving measures of maximum and explosive strength (Lyttle, Wilson & Ostrowski, 1996; Newton et al., 2002).

#### 2.34 Participant variables that mediate adaptations to resistance training

The initial training status of the participants influences the strength improvements gained from a resistance training intervention. In general, those participants with lower initial strength levels produce the greatest gains (Eisenman, 1978; Wilson, Murphy & Walshe, 1997), and therefore most resistance training programmes will cause an improvement in untrained participants. Conversely, with trained participants the principle of diminishing returns applies with respect to the potential for strength adaptations to a resistance training stimulus. However, increases in strength have been reported for resistance-trained athletes during a long-term programme (Häkkinen et al., 1988). The magnitude of the strength gained as a result of long-term resistance training may be limited by phenotypic factors. For

example, those participants with a high proportion of slow-twitch muscle fibres may have a reduced ability to increase maximum power output even following a resistance training programme combining high-force and high-velocity exercises (Newton et al., 2002).

Although those participants who are initially weakest tend to produce the greatest strength gains following a resistance training intervention, it is not clear how the magnitude of the gains in strength affect the performance on tasks that were not specifically trained. For example, Olsen and Hopkins (2003) reported that those participants who demonstrated the greatest increase in maximum strength (1-RM bench-press) changed little on a task requiring strength that involved similar muscle groups (a palm-strike movement). This finding may be caused by the specificity of the adaptations to a resistance training intervention.

### 2.35 Specificity of strength gains

It is generally acknowledged that the gains in strength attained from a resistance training intervention are greatest in the movements used during training. The specificity of strength gains has been demonstrated with respect to posture (Wilson, Murphy & Walshe, 1996), the type of muscle action used in the training and testing exercises (Abernethy & Jurimae, 1996; Rutherford & Jones, 1986), in open versus closed-kinetic chain exercises (Augustsson et al., 1998; Carroll et al., 1998), and in bilateral versus unilateral movements (Häkkinen et al., 1996; Häkkinen & Komi, 1983). The activation of motor units during movements is affected by the posture adopted (Brown, Kautz & Dairaghi, 1996; Person, 1974) and the direction of force applied during a given movement (Ter Haar Romeny, van der Gon & Gielen, 1982, 1984) and so the specificity effects of resistance training are believed to be a result of adaptations in the motor commands during the training movements (Duchateau & Enoka, 2002). Therefore, the similarities between the training and assessment movements have significant implications for the gains in strength achieved from a resistance training intervention.

The specificity effects of resistance training may also be related to the magnitude of the strength gains. Carroll et al. (1998) found that isoinertial resistance training performed 3-times per week produced a significant increase in isoinertial strength assessed in a specific training movement (back squat), but did not increase isokinetic leg extension strength, a movement that was not used in training. The same training programme performed twice a week over a longer period (equal training volume) produced a significant improvement in both measures of strength. However, those participants that trained 3-times per week made

greater increases in the back squat assessment. The authors proposed that the increased frequency of training that had resulted in the greater magnitude of strength gains had enhanced a specific muscle activation pattern that was appropriate to the squat exercise but was not conducive to increasing strength in the leg extension movement. Although this hypothesis was not directly tested by Carroll et al. (1998), the specificity of increased muscle activation in trained movements with little change in untrained movements has been demonstrated elsewhere (Häkkinen & Komi, 1983; Thepaut-Mathieu et al., 1988). Similarly, Baratta et al. (1988) reported that 3-weeks of resistance training using a knee flexion movement increased knee flexor EMG activity during a maximum strength knee extension task. Although not tested directly, the increased knee flexor activity would reduce the knee extension torque, and so interfere with the performance of the knee extension task. Thus, neuromuscular adaptations appear to optimise only the practiced movements and not other movements in which the neuromuscular elements are involved (Bawa, 2002). This has significant implications for the reformatory effects of resistance training on sprint running.

### 2.36 Summary

The mechanical expressions of strength depend upon the complex interaction of phenotypic and neural factors that are influenced by the stimulus of resistance training. Increases in muscular strength are evident following resistance training interventions lasting as little as 2 weeks. Neural adaptations dominate the increases in strength observed in the early phases of a resistance training programme, although adaptations in sarcomeric proteins may also influence the expressions of strength at this time. The extent of the adaptations to resistance training depends upon the design of the training programme and the initial training status of the participant. Periodised resistance training programmes appear to be effective at increasing muscular strength and the combination of high force and high velocity sessions has been recommended to improve the transfer of strength to sports requiring strength and speed. The co-ordination of activity between muscles has a significant influence on the expression of strength, and it appears that changes in the task constraints (muscle action associated with the training and testing exercises) influence the performance improvements gained from a resistance training regime. Specifically, the increased strength gained from a resistance training intervention may not transfer to other tasks if the training exercises involve unrelated movement patterns. The magnitude of the strength gains may influence the transfer of strength to untrained movements, although research is lacking.



## **2.4 The effects of resistance training on accelerative sprinting**

There is a paucity of research of the influence of resistance training on accelerative sprinting. The studies presented in Table 2.3 are those that investigated the effects of resistance training in the absence of formal sprint training, while those in Table 2.4 have combined resistance training and sprint training. For both sets of studies, effect sizes (ES) have been calculated based on the published means and standard deviations of the groups (Thomas, Salazar & Landers, 1991). This measure provides an estimate of the magnitude of the changes reported.

The studies presented in Table 2.3 show mixed findings, most likely due to the different resistance training regimes and the different participant samples used. None of the studies summarised have assessed the effects of resistance training on sprint-trained participants. It is noticeable that the changes in sprint performance are not as great as those for the measures of strength, particularly maximum strength. It appears that a resistance training regime that produces greater increases in explosive strength compared to maximum strength is more likely to improve accelerative sprint performance (cf. Fry et al., 1991; McBride et al., 2002). The explanation for this may be that the sprinting performance requires increased force capabilities during high velocity movements, similar to the measures of explosive strength. Resistance training regimes involving only heavy loads appear detrimental to initial acceleration performance compared to training with relatively light loads. For example, McBride et al. (2002) reported a significant increase in 10 m following a period of resistance training using heavy loads (80% 1-RM), while an improvement in sprint performance was realised following resistance training using relatively lighter loads (30% 1-RM). Despite the significant increase in 10 m time following the heavy resistance training, these authors noted only a slight increase in 20 m time (less than the increase in 10 m time), suggesting that the heavy resistance training improved performance over the second 10 m of the 20 m sprint. For the participants used in this study, these two distances are likely to represent 2 distinct phases – the initial acceleration and the maximum velocity phases. This highlights the different qualities associated with the different sprint phases and the importance of assessing sprint performance over intermediate distances. It could be argued that a resistance training intervention using a combination of heavy and light loads could improve performance over the entire 20 m trial, given that the light load group improved performance over the initial 10 m while the heavy load group improved performance over the second 10 m.

**Table 2.3** Studies of the effects of resistance training on accelerative sprinting.

Authors	N	Programme details	Sprint performance		Maximum strength		Explosive strength	
			Measure	% change* (ES)†	Measure	% change* (ES)†	Measure	% change* (ES)†
Fry et al. (1991)	10	12 weeks. Weight training 3.wk <sup>-1</sup> , plyometrics 2.wk <sup>-1</sup> ‡	9.1 m time	↑ 9% (0.59)	1-RM squat	↑ 21% (1.18)	CMJ height	↑ 7% (0.66)
Hennessy & Watson (1994)	9	8 weeks. Weight training 3.wk <sup>-1</sup> ‡	20 m time	↓ 1% (0.47)	1-RM squat	↑ 17% (1.26)	CMJ height	↑ 6% (0.67)
McBride et al. (2002)	9	8 weeks. JS 30% 1-RM squat. 2.wk <sup>-1</sup>	10 m time	↓ 2% (0.75)	1-RM squat	↑ 8% (1.20)	PP SJ 30% 1-RM PP SJ 80% 1-RM	↑ 10% (1.60) ↑ 18% (2.83)
	10	8 weeks. JS 80% 1-RM squat. 2.wk <sup>-1</sup>	10 m time	↑ 5% (2.75)	1-RM squat	↑ 11% (1.52)	PP SJ 30% 1-RM PP SJ 80% 1-RM	↑ 4% (0.67) ↑ 14% (2.01)
Rimmer & Sleivert (2000)	10	8 weeks. Plyometric sessions. 2.wk <sup>-1</sup>	10 m time	↓ 3% (0.55)		NA		NA

Note: \* Average percentage change for groups; † ES = Effect Size, calculated using the method outlined by Thomas, Salazar & Landers (1991). ‡ Periodised training programme. N = number of experimental participants; 1-RM = one repetition maximum; CMJ = countermovement vertical jump; SJ = static vertical jump; PP = peak power output.



Studies that have investigated the effects of a combination of resistance and formal sprint training on accelerative sprinting are shown in Table 2.4. The inclusion of sprint training is believed to increase the transfer of strength gains to the sprint performance (Delecluse, 1997) and the inspection of the findings appears to confirm this, with 3 studies reporting substantial improvements in accelerative sprint performance (Andersen et al., 1994; Blazevich & Jenkins, 2002; Delecluse et al., 1995b).

In non sprint-trained participants the combination of resistance training and sprint training appears to be effective in improving accelerative sprint performance, although only when sprint-specific resistance exercises are used (Delecluse et al., 1995b). However, the improvements in sprint performance may be short-term. For example, Gorostiaga et al. (2004) reported that the improvement in 5 m sprint time found after 4-weeks of a combined resistance and sprint training intervention was lost by the eighth and eleventh weeks of training. These authors reported significant correlations between the relative change in explosive strength and the relative change in average velocity over both 5 m ( $r = 0.86$ ) and 15 m ( $r = 0.95$ ) assessed after 4-weeks of the intervention, suggesting that the greatest gains in accelerative sprinting are realised by those participants who demonstrate the greatest gains in explosive strength. Thus, the magnitude of strength gains may mediate the influence of resistance training on accelerative sprint performance when resistance and sprint training are combined, certainly in non sprint-trained participants.

In trained sprinters improvements in accelerative sprint performance can be achieved using either heavy or light resistance training combined with sprint training (Blazevich & Jenkins, 2002). However, the improvements may be specific to the acceleration phase of sprinting, with no change in maximum velocity sprinting (flying 30 m time) reported despite improvements in acceleration (Andersen et al., 1994). An important aspect of the study by Andersen et al. (1994) was the inclusion of muscle biopsies to determine any changes in muscle fibre characteristics of the VL muscle. The analysis revealed that there was a decrease in pure fibres containing MHC I isoform, an increase in the pure fibres containing MHC IIa isoform and an increase in hybrid fibres containing both MHC isoforms IIa and IIb. It was concluded that sprint and strength training produce 'faster' muscle fibres that are suitable for strength-demanding performance, although it is difficult to separate the specific effects of the resistance and sprint training on these phenotypic adaptations and how they contributed to the performance improvements reported.

**Table 2.4** Studies of the effects of resistance training combined with sprint training on accelerative sprinting.

Authors	N	Programme details	Sprint performance		Maximum strength		Explosive strength	
			Measure	% change* (ES)†	Measure	% change* (ES)†	Measure	% change* (ES)†
Andersen et al. (1994)	6	12 weeks. Heavy resistance 2.5.wk <sup>-1</sup> , plyometrics 1.wk <sup>-1</sup> , interval training 2.5.wk <sup>-1</sup> ‡	20 m time	↓ 1.5% (0.86)	NA	NA	NA	NA
			30 m time	↓ 2% (0.81)				
Blazevich & Jenkins (2002)	5	7 weeks. High-velocity resistance (30% - 70% 1-RM) 2.wk <sup>-1</sup> , ¶ sprint training‡	20 m time	↓ 4% (0.93)	1-RM squat	↑ 12% (1.02)	NA	NA
	4	7 weeks. Low-velocity resistance (50% - 90% 1-RM) 2.wk <sup>-1</sup> , ¶ sprint training‡	20m time	↓ 3% (1.19)	1-RM squat	↑ 12% (0.69)	NA	NA
Delecluse et al. (1995b)	22	9 weeks. Heavy-resistance 2.wk <sup>-1</sup> , ¶ sprint training 1.wk <sup>-1</sup>	10m acceleration	↑ 1% (0.07)	NA	NA	NA	NA
	21	9 weeks. Plyometric sessions 2.wk <sup>-1</sup> , sprint training 1.wk <sup>-1</sup>	10 m acceleration	↑ 7% (1.12)	NA	NA	NA	NA
Gorostiaga et al. (2004)	8	4 weeks. Resistance training 2.wk <sup>-1</sup> , ¶ sprint training 1.wk <sup>-1</sup>	5 m time	↓ 1% (0.28)	NA	NA	CMJ 0 height	5% (1.73)
			15 m time	↓ 0.4% (0.14)			CMJ60 height	11% (0.69)

Note: \* Average percentage change for groups; † ES = Effect Size, calculated using the method outlined by Thomas, Salazar & Landers (1991); ‡ Participants were elite sprinters, but the specific frequency of sprint training or the session details are not available. ¶ Periodised training programme. N = number of experimental participants; 1-RM = one repetition maximum; CMJ 0 = unloaded countermovement vertical jump; CMJ60 = countermovement vertical jump with 60 kg load.

## 2.41 Summary

There exists little evidence demonstrating a consistent improvement in accelerative sprinting following an intervention of resistance training only. As most studies have been performed on untrained sprinters it has been suggested that the modest improvements in sprint performance may reflect the pre-training sprinting ability of the study participants, rather than any failure of the resistance training programme (Hoffman, 2002). While this claim is difficult to substantiate, especially when changes in appropriate measures of strength are not always reported, there appears to be an influence of resistance training on accelerative sprint performance that is mediated by the sprint capabilities of the participants. The magnitude of strength gains may also influence the effect of resistance training on sprint performance.

With few studies performed, each employing diverse designs, it is difficult to ascertain which resistance training method is most effective at improving accelerative sprinting. An intervention of only explosive-type resistance training may confer statistically significant, but practically unsubstantial improvements in untrained sprinters. For trained sprinters, both explosive and heavy resistance training methods appear to be effective in improving accelerative sprint performance when combined with sprint training. However, if the effect of resistance training on performance during the acceleration phase of sprint running is to be investigated then appropriate measures of strength are required to allow the effectiveness of the resistance training intervention to be assessed.

It is important to note that no study has attempted to control the starting position of the participants during the sprint performance. As mentioned previously, the starting position has a great influence on the accelerative sprint performance and therefore a control for this variable should be implemented in future studies. Issues of familiarisation and reliability of the sprint measures are often ignored, and so assessing the true change in performance is difficult (Hopkins, 2000). Coefficients of variation of 1.8% and 2.2% have been reported for 10 m and 20 m sprint times, respectively, from a standing start without the need for familiarisation sessions in physically active men (Moir et al., 2004). These reliability statistics bring the magnitude of the changes in sprint performance presented in Tables 2.3 and 2.4 into question.

Possibly the greatest failing of the extant research is in the reliance on outcome measures in the assessment in changes in sprint performance following a resistance training intervention. This is particularly important when attempting to explain why the strength gained from a

resistance training intervention may or may not have been transferred to sprint performance. The analysis of sprint time or related variables does not allow adequate explanations to be forwarded. One previous study attempted to assess the changes in kinematic variables (stride length, rate and stance time) associated with accelerative sprint performance (Rimmer & Sleivert, 2000). However, because of reliability problems the authors were unable to identify changes in these variables. These kinematic stride measures represent the minimum requirement, particularly given the determinants of stride length and stride frequency during sprinting (Hunter et al., 2004a). If the issue of transfer of strength gains to accelerative sprinting are to be adequately explained then more in-depth measures are required.

## **2.5 Co-ordination and control of movement**

Having reviewed the relevant literature it is pertinent to question why increases in muscular strength do not typically transfer to accelerative sprint performance, particularly in untrained sprinters. To investigate this there is a need for assessment beyond simple outcome measures such as sprint time. The processes associated with the sprinting movement that are influenced by resistance training should be delineated.

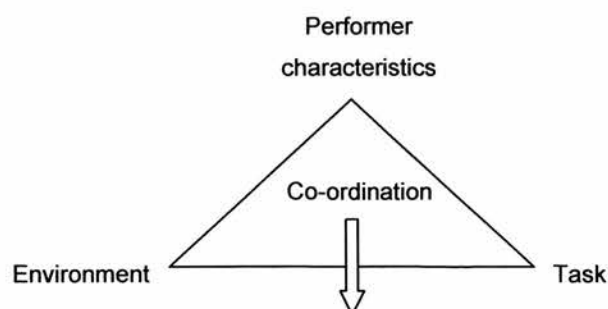
The specificity of the adaptations to resistance training interventions has been highlighted. It has been shown that the activation of motor units is affected by the direction of force application and posture (Brown et al., 1996; Person, 1974; Ter Har Romeny et al., 1982, 1984). As such, the similarities in movement patterns between the resistance training exercises and the performance task are likely to influence the transfer effects of resistance training. This is important given the identification of the control of the direction of the GRF as a specific constraint during the stance periods of accelerative sprinting (Jacobs & Van Ingen Schenau, 1992). Short-term resistance training can have a negative impact on related movements, as evidenced by the interference in certain tasks reported in the studies of Baratta et al. (1988) and Carroll et al. (1998), with neural mechanisms proposed as responsible. The influence of neural adaptations to resistance training on the transfer of learning has recently been reviewed by Carroll et al. (2001b). These authors concluded that resistance training induces neural adaptations that are associated with learning the optimal pattern of muscle recruitment for the training movements. Moreover, the enhancements of muscle co-ordination from the training movements could negatively influence the pattern of muscle recruitment during untrained strength tasks (negative transfer). However, positive transfer could occur if the learning of the optimal pattern of muscle activity for the resistance training exercises strengthens the excitatory neural connections between the muscles that act

as synergists during the transfer task, or if the learning reinforces inhibitory circuits between muscles that, if activated together, would degrade performance. Thus, resistance training causes adaptations in neural elements that will affect the co-ordination and execution of movement during a range of tasks (Carroll et al., 2001b). Accordingly, following a period of resistance training, one may expect changes in the co-ordination of movement tasks.

Some authors have intimated that a lag time exists between the transfer of strength gains to selected performance tasks, such as sprinting (Stone et al., 2002). It is proposed that this lag time is associated with the participants of a resistance training regime ‘learning’ to apply their increased strength capabilities in other performance tasks. How long this lag time may last is a matter of debate. However, the duration of the studies investigating the effect of resistance training on accelerative sprint performance reviewed here range from 4-weeks (Gorostiaga et al., 2004) to 12-weeks (Fry et al., 1991). It is possible that these relatively short durations are sufficient to elicit significant increases in measures of strength but not long enough for these improvements to impact on more complex tasks, such as sprinting (Delecluse, 1997).

### 2.51 Physical constraints shaping co-ordination

The notion of learning to apply increased strength capabilities has obvious implications for the co-ordination of movement. In a constraints-led approach to movement co-ordination based within a dynamical systems framework (Clark, 1995; Handford et al., 1997), co-ordination patterns are shaped by limitations (constraints) specified by the task, the environment and the physical characteristics of the performer (Newell, 1986) (Figure 2.10).



**Figure 2.10** Movement co-ordination emerges from the constraints specified by the task, the environment and the physical characteristics of the performer. Adapted from: Newell (1986).

The dynamical systems perspective offers a valuable approach to understanding the processes underpinning co-ordination, particularly following a change in physical

constraints. The motor system is able to adapt to many changes in the physical constraints such as a loss of structure, a loss of proprioception, a change in muscular strength, or increases in limb dimensions. Under such conditions the motor system is able to alter the patterns of co-ordination to allow the production of the required movements. These co-ordination patterns can be considered 'optimal' to allow the movement task to be achieved given the physical constraints of the motor system (Holt, Fonseca & LaFiandra, 2000; Latash & Anson, 1996). Moreover, the patterns of co-ordination that emerge are specified by and facilitate the use of sources of energy (e.g. muscular force, co-contraction, mechanical properties of tissues) available to the individual for a given task (Holt, Obusek & Fonseca, 1996). Some authors have suggested that these patterns develop because of the redundancy of the motor system (Latash & Anson, 1996). As such, movement co-ordination is an *a posteriori* result of the confluence of constraints associated with the motor system.

#### 2.511 Physical constraints affecting locomotor tasks

How the motor system adapts to changes in physical constraints to produce movements can be investigated by assessing the performance of amputee patients, anterior cruciate ligament (ACL) injury patients, the elderly, and children during locomotory tasks.

##### 2.5111 Amputee gait

Unilateral, below-knee amputation confers substantial losses of structural and sensory components of the motor system, with the elimination of musculature and proprioceptors residing in the amputated portion of the leg. Such losses cause significant changes in the joint moment and reflex contributions during gait. Although amputation represents an extreme change in the physical constraints associated with the motor system, it has been demonstrated that the changes are able to be accommodated by altering other parameters such that the relative timing of the movement is preserved. For example, during gait in healthy participants the ankle plantar flexors are the major energy generators. These muscles are absent in the below-knee amputee patient and so an adaptive response is seen in an increased activity of the hip extensors to generate and absorb energy during gait (Czerniecki, Gitter & Munro, 1991). Other researchers have reported that the motion of the prosthetic limb of the amputee patient is incorporated with that of the intact limb, producing symmetrical gait during walking and running over a variety of velocities (Enoka, Miller & Burgess, 1982; Sanderson & Martin, 1996; Sanderson & Martin, 1997). The symmetrical gait is maintained by modulating the joint moments of the intact leg to correspond to those of the prosthetic leg (Sanderson & Martin, 1996; Sanderson & Martin, 1997). However, it has



been shown that the formation of new joint moment patterns of the intact limb was not necessary, but rather the magnitude of the existing joint moments was altered to accommodate the new properties of the affected limb (Sanderson & Martin, 1996). As a result, the timing of the kinematic patterns of the 3 lower limb joints (hip, knee, and ankle) during the gait cycle is maintained.

#### 2.5112 Locomotion following ACL injury

Following ACL rupture, patients experience a loss of proprioceptive function and/or reduced strength of the muscles around the knee. This can lead to instability at the knee joint which can cause episodes of 'giving way' during weight acceptance (Buss et al., 1995; Daniel et al., 1994). This has significant implications for gait, and ACL deficient patients have been shown to compensate by reducing knee flexor and knee extensor moments during the stance periods of walking (Berchuck et al., 1990; Rudolph et al., 1998). When comparing ACL-deficient patients to healthy controls, Lewek et al. (2002) reported that both groups walked and jogged at the same self-selected speeds. However, the ACL-deficient patients achieved the locomotion with reduced knee flexion moments.

#### 2.5113 Locomotion of the elderly

Aging is associated with a number of adaptations within the neuromuscular system that affect movement performance. For example, a decrease in muscular strength, a loss of motor units, a shift towards a higher percentage of type I muscle fibres and a decrease in the flexibility of soft tissue have been shown in elderly populations in comparison with their younger counterparts (Luff, 1998; Maharam et al., 1999; Porter et al., 1995). Moreover, differences in co-ordination patterns during locomotor tasks exist between young and elderly populations. For example, reduced step length and speed during walking tasks in elderly populations are proposed to be a result of neuromuscular adaptations to the aging processes (McGibbon, 2003). When analysing sprint running, Roberts et al. (1997) found that elderly runners produced maximal sprint velocities that were less than those produced by younger runners. Analysis of the thigh and shank velocities and joint moments during the flight period of a stride cycle revealed that the pattern of the kinematic and kinetic data were similar between the two populations. However, the elderly runners produced the movement with lower peak angular velocities and joint moments. It was suggested that the elderly runners preserved the overall kinematic pattern of the stride cycle by reducing the range of motion of the limb segments through reductions in the appropriate joint moments. The reductions in the range of motion were necessary to ensure that the timing of the swing limb



corresponded to that of the stance limb. The reduced force capabilities of the elderly runners resulted in an increased stance duration of the contralateral limb and so the joint moments of the swing leg were adapted to maintain the overall kinematic pattern of the stride cycle.

#### 2.5114 Locomotion of children

Studies of amputee, ACL injury and elderly populations demonstrate that the motor system adapts to changes in physical constraints by altering certain aspects of co-ordination to produce the required movements. Often the patterns of co-ordination are simply re-scaled to accommodate the changes in the physical constraints of the motor system, with alterations in the behaviour at certain joints while the overall pattern of co-ordination is maintained (e.g. Lewek et al., 2002; Roberts et al., 1997; Sanderson & Martin, 1996). However, the cross-sectional nature of the studies prevents the analysis of the processes associated with adaptation. Longitudinal studies of children offer insights to the process of adaptation to changes in the physical constraints of the motor system. The developing child experiences great changes in physical parameters including increases in body mass, muscular strength, limb dimensions and changes in body composition (Borms, 1986; Haywood & Getchell, 2001; Kondric & Misigoj-Durakovic, 2002). Such changes are likely to impact on the movement capabilities of the child. Indeed, periods of high velocities in physical growth have been found to be negatively related to motor competence in tasks including manual dexterity and balance (Visser, Geuze & Kalverboer, 1998). In a longitudinal study of hopping performance in children over a 15-year period, Robertson and Halverson (1988) were able to identify several qualitatively distinct co-ordination patterns as the children developed, and so identify developmental sequences for the movement task. The observed changes were proposed as a result of alterations in the physical characteristics such as limb length, stiffness and mass. Despite the changes observed in co-ordination, the authors reported relative timing invariants during the movement. For example, the percentage of total cycle time spent in the support and flight periods of the hop remained relatively constant across the study period. Similarly, the percentage of the support period between landing and greatest knee flexion remained invariant across the different developmental sequences identified by the authors. In an investigation of the development of intralimb co-ordination of infants during the first year of independent walking, Clark and Phillips (1993) reported qualitatively distinct co-ordination patterns as development proceeded. A comparison of the patterns of the infants and adults during the task also revealed distinctions. However, as the infants developed, the co-ordination patterns began to resemble those of the adults. The effect was such that by 3-months of walking the infants displayed an adult-like intralimb co-ordination pattern. These

two longitudinal studies demonstrate that the co-ordination patterns during the selected multi-joint movements were altered in accordance with the changes in the physical constraints, producing qualitatively distinct patterns. Therefore, co-ordination patterns emerge that are specified (in part) by the physical constraints of the motor system.

#### 2.512 Mechanical properties of muscles constraining co-ordination

There is evidence from simulation studies that the mechanical properties of the muscles are important in determining the appropriate co-ordination pattern for a given task. For example, Pandy (1990), simulating a vertical jump for maximum height, reported that changing the properties of the effectors (increasing muscle-fibre contraction velocity or body strength-to-weight ratio) caused a delay in the extension of the lower limb joints. Similar results were reported by Bobbert and Van Soest (1994), again simulating the vertical jump. However, these authors went further and reported that strengthening the active muscles did not produce improved performance (increase in jump height) unless the timing of the muscle activations was concomitantly adapted to the new muscle properties. The authors concluded that muscle training exercises should be accompanied by exercises that allow athletes to practice with their changed muscle properties if jump height is to be improved. This is in agreement with the suggestion of other authors that a period of learning to use strength is required following a resistance training intervention (Stone et al., 2002). For an improvement in accelerative sprinting to be realised it is possible that new muscle activation patterns are required to capitalise on the gains in strength accrued from a resistance training intervention. The development of new patterns of activation may be manifest in a change of the co-ordination pattern associated with the sprinting movement.

Despite the results from simulation studies, identifying the role of mechanical properties of muscles in the co-ordination patterns during real-life movements poses a more difficult task. However, the inability to exploit muscular force has been identified as one of a number of physical characteristics that results in the gait deficiencies (smaller amplitudes, shorter stance periods) observed in children with spastic hemiplegic cerebral palsy (Holt et al., 2000). Similarly, the mechanical properties of muscle have been identified as important factors in determining the resonant frequency during a hopping task (Bach et al., 1983). Carson and colleagues (Carroll et al., 2001a; Carson, 1996; Carson & Riek, 1998) have highlighted the potential role of muscular constraints influencing co-ordination during sensory-motor tasks. They have shown that both acute and chronic changes in force generating capacity of the active muscles can affect the stability of movement co-ordination.

For example, acute changes in force arising from a change in muscle length and moment arm confer a predictable influence on the movement frequency at which an extend-on-the-beat pattern of finger co-ordination is compromised (Carson, 1996; Carson & Riek, 1998). Chronic changes in the strength of the extensor muscles of the fingers as a result of resistance training have been shown to enhance the stability of the extend-between-the-beats co-ordination pattern (Carroll et al., 2001a). The authors proposed that the enhanced stability was due to a lower level of cortical input to the spinal motoneurons required to generate a particular level of muscle activation. It is important to note that the movements used in the resistance training programme were the same used in the sensory-motor performance task. Therefore, it is known that increasing muscular strength by performing resistance training exercises that are specific to the movement task can enhance the stability of the co-ordination of movement, certainly in single-joint sensory-motor tasks. If the stability of the co-ordination pattern is enhanced as a result of resistance training then this would have implications for sprint tasks characterised by high spatio-temporal constraints, such as the run-up in long jumping (Glize & Laurent, 1997).

Beyond simulation studies, there is a paucity of research of how changes in muscle properties affect co-ordination during multi-joint tasks. In relation to sprint running, it has been shown that transient changes in the mechanical properties of the muscles caused by fatigue elicit changes in the kinematic and kinetic characteristics of movement during the sprint stride (Pinniger, Steele & Groeller, 2000; Sprague & Mann, 1983). However, there is no research investigating the effects of resistance training on the co-ordination of the sprinting movement. The results of computer simulation models predict that increasing muscular strength will not improve performance unless there is a concomitant change in the muscle activation pattern (Bobbert & Van Soest, 1994), revealed in the pattern of co-ordination. However, it should be acknowledged that computer simulation models represent heuristic devices that may not adequately reflect co-ordination changes in real-life, multi-joint movements.

A prediction from a dynamical systems perspective would be that a new co-ordination pattern is developed based upon the physical constraints imposed on the motor system. However, if an appropriate co-ordination pattern exists then certain aspects of the pattern may simply be re-scaled to satisfy the task demands. The non-linear mechanical properties of the muscles (force-length-velocity relationships) provide a mechanism for adapting to different internal and external demands (Chapman & Sanderson, 1990; Gerritsen et al.,

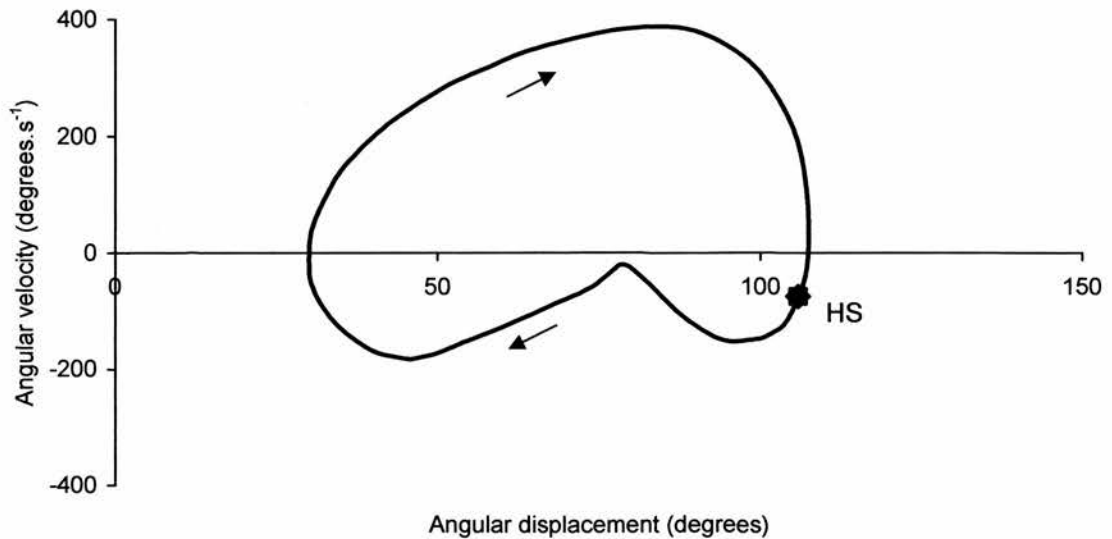
1998), and so small increases in muscular strength are likely to be accommodated into the original co-ordination pattern. In order to approach such an issue it is important to define appropriate measures of co-ordination.

### 2.513 Co-ordination measures

Co-ordination patterns are the result of the individual components of the motor system (muscles, neural pathways) working collectively to achieve an outcome that is commensurate with the constraints associated with the environment, the task and the motor system itself. This collective organisation leads to the formation of co-ordinative structures, the functional coupling between constituent components of the motor system (Kugler et al., 1980). Within these co-ordinative structures the individual muscles compensate to preserve the relationship of the collective unit in the face of changing system behaviour (Tuller et al., 1982). In this way, the redundancy problem of the motor system is solved and the processing burden of the CNS during movement tasks is reduced. Changing the physical constraints of the motor system may require the construction of a new co-ordinative structure which allows successful movement with respect to the task demands once the appropriate level of constraint has been imposed. Such a scenario is typical during development as evidenced in the qualitatively distinct co-ordination patterns reported previously (Clark & Phillips, 1993; Robertson & Halverson, 1988). As such, development can be regarded as a period of continually developing co-ordinative structures and making temporary states of co-ordination resistant to elements that could perturb the stability of the system (Handford et al., 1997). During this period of development, dramatic changes in movement form may be observed. However, when the co-ordination patterns for the task have been established and stable co-ordinative structures operate under imposed constraints, changes in the physical constraints may only require a re-scaling of certain parameters in order to successfully meet the demands of the task. As such, changes in behaviour at certain joints can occur (e.g. a decrease in the range of motion) while the overall pattern of co-ordination is maintained for the movement.

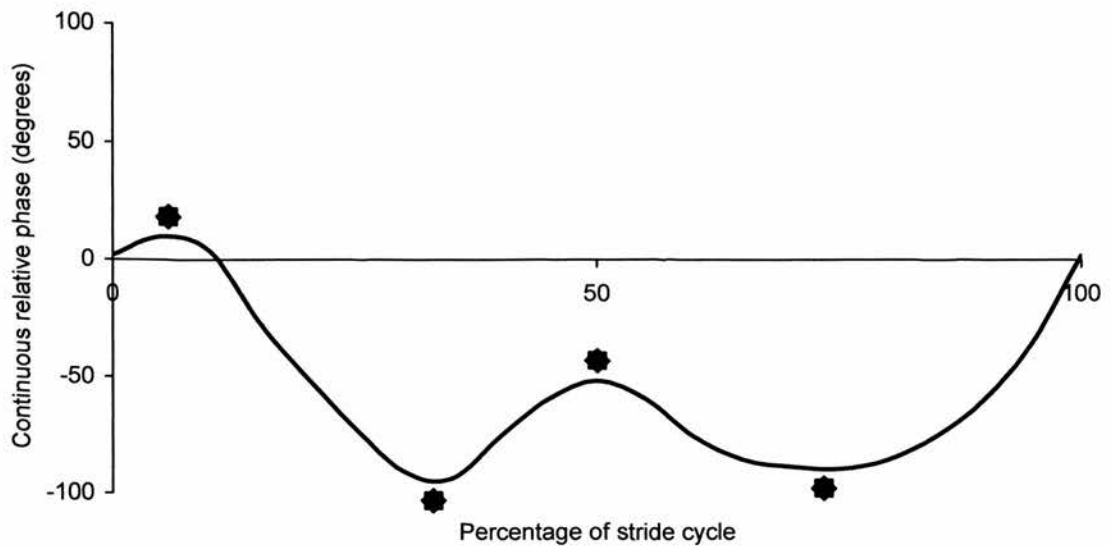
A dynamical systems perspective of movement co-ordination emphasises the identification of control and order parameters. An order parameter is a low-dimensional variable that defines the state of the system (Clark, 1995; Handford et al., 1997). The selection of an appropriate order parameter is essential as changes in the order parameter provide a measure with which changes in co-ordination can be evaluated. If the body segments are considered as component oscillators following the principles of thermodynamics during multi-joint

movements (Kugler et al., 1980) then the behaviour of the segments can be adequately described using phase-plane diagrams. Phase-plane diagrams plot the angular velocity of a joint or limb segment as a function of limb position. The oscillations of the lower limb segments (shank and thigh) during gait have been summarised in phase-plane diagrams, showing the behaviour of limit-cycle oscillators with closed, periodic trajectories (Clark & Phillips, 1993). An example of a phase-plane diagram is shown in Figure 2.11.



**Figure 2.11** Phase-plane diagram for the shank during walking. The diagram evolves in a clockwise direction from heel-strike (HS). From: Barela et al. (2000).

Modifications in the shape of the diagram trajectory represent new behaviours of the motor system. The coupling of two limit-cycles can be expressed through relative phase (RP) measures. Such measures have been identified as an order parameter that defines the dynamic state of the neuromuscular system during gait (Barela et al., 2000; Clark & Phillips, 1993; Hamill et al., 1999; Van Emmerik & Wagenaar, 1996a, 1996b). Continuous relative phase (CRP) provides spatial and temporal information (Hamill, Haddad & McDermott, 2000) and has been shown to be a more sensitive measure in detecting changes in co-ordination than kinematic joint trajectories during gait cycles (Barela et al., 2000). CRP measures can be used to assess intralimb (the joints/segments of a limb) and interlimb (upper and lower limb or contraateral, homologous limbs) couplings. An example CRP graph for intralimb co-ordination during gait is shown in Figure 2.12. The local minima and maxima in the CRP trajectory represent reversals in the co-ordination dynamics between the components of the motor system.



**Figure 2.12** Continuous relative phase for the thigh-shank coupling during a single stride of walking at a preferred speed. Reversals in the co-ordination of the segments are highlighted (★). From: Barela et al. (2000).

A control parameter is a constraint which, when changed in scale, causes a reorganisation of the system dynamics reflected in a qualitative change in the order parameter (Clark, 1995; Handford et al., 1997). Control parameters exist in the task, the environment and the performer. For example, an increase in the oscillatory frequency of limb segments (a change in a task constraint) elicits a spontaneous change in the behaviour of the system, manifested in a change in the RP between the segments (Kelso, 1984). As such, frequency has been identified as a control parameter in many tasks (Diedrich & Warren, 1995; Haken, Kelso & Bunz, 1985; Van Emmerik & Wagenaar, 1996a). From the preceding discussion it is clear that changes in the neuromuscular system (physical constraints) can represent potent control parameters. Indeed, Thelen (1986) identified muscular strength as one of a number of control parameters limiting the development of upright locomotion in children. For the present thesis, an increase in muscular strength, as a control parameter, may induce a change in the co-ordination during a given task, revealed in a change in the order parameter. These changes will be evident in the phase-plane diagrams and/or the RP measures recorded during the movement.

Changes in co-ordination may not occur immediately in response to a change in the control parameter, and there may be a period of exploration as the motor system searches for an appropriate co-ordination pattern to perform the movement. The exploration of different co-



ordination patterns provides perceptual information which guides the selection of the appropriate pattern to satisfy the task constraints (Fitch et al., 1982). During this period of exploration, higher-order derivatives of positional information are proposed to provide the necessary information (Cox, 1991). When learning a multi-joint kicking task, participants were reported to produce greater joint angular jerk and snap measures (the third and fourth time derivatives of position, respectively) as learning continued (Young & Marteniuk, 1997).

During the acquisition of skill in a drop jumping task on a compliant surface, Sanders and Wilson (1992) reported that the Fourier spectra of the relative CoM acceleration changed such that the amplitude of the higher frequency harmonics increased with practice. The performance (height) of the drop jump task improved during the practice period and was accompanied by a gradual change in the pattern of co-ordination. The higher frequency harmonics enabled the composite waveform of the relative acceleration to develop 'sharper' characteristics, enhancing the rate of increase and decrease of the relative acceleration to produce a more optimal pattern of forces. The authors suggested that the addition of higher frequency components in the movement was indicative of the participants 'fine tuning' the performance. The appearance of higher frequency components in the trajectory of the centre of pressure during postural tasks has been ascribed a functional role in dissipating instabilities due to external perturbations and/or in exploring new patterns (Riccio, 1993). The exploratory behaviour is proposed to occur on spatial and temporal scales that are smaller than those characteristic of the performatory behaviour so as not to interfere with the movement task, and so higher frequency components of the movement signals emerge (Riccio, 1993). Therefore, recording changes in frequency composition of the movement trajectories may provide insight into how the motor system adapts to a change in a control parameter to optimise the movement.

Instabilities in the patterns are important features during change in co-ordination as they are indicative of the system exploring possible co-ordination patterns to account for structural or dynamic alterations (Riccio, 1993; Schöner et al., 1992). The instabilities are marked by increased variation in the co-ordination pattern. For example, the early movement patterns of infants during a walking task showed marked instabilities but developed into the more stable patterns used by adults as the infants developed (Clark & Phillips, 1993). Prior to a transition in co-ordination there is a loss of stability, manifest by an increase in the variance or standard deviation of RP measures (Haken et al., 1985; Schöner & Kelso, 1988). For example, the walk-run transition is preceded by a period of instability in the intralimb co-



ordination pattern, evidenced by an increase in the variability of discrete measures of RP, as the motor system evolves from the walking to the running action (Diedrich & Warren, 1995). However, previous research using single-joint movements have reported a reduction in the variability of co-ordination following a resistance training intervention due to reduced cortical input required to perform the particular movements (Carroll et al., 2001a). Accordingly, measures of variability associated with the co-ordination patterns can provide useful information pertaining to the state of the motor system and its readiness to change co-ordination patterns and the transfer of neural adaptations to a resistance training intervention.

Because each individual has different physical characteristics constraining the motor system unique movement strategies are likely to be identified for a given task despite similarities in performance levels. For example, Burden, Grimshaw and Wallace (1998) reported large inter-individual variations in the swing movement of golfers of a similarly high standard. As well as unique movement strategies, individual differences are likely to occur during co-ordination changes. For example, Yang, Winter and Wells (1990) reported that different perturbations during a postural task were countered by very different joint torque strategies in the participants, while Van Emmerik and Wagenaar (1996a) found individual differences in the changes in co-ordination of the pelvis-thorax rotations in response to increases in walking velocity. Therefore, analysing changes in co-ordination across group means may mask important individual adaptations.

#### 2.52 Implications for resistance training and sprinting performance

A resistance training regime would be expected to increase muscular strength through the various phenotypic and neural adaptations already highlighted in this review. In a dynamical systems perspective of movement co-ordination, muscular strength can be considered as a control parameter acting to constrain the behaviour of the motor system which will be manifest in the co-ordination pattern (the order parameter). An appropriate pattern of co-ordination emerges for a given movement that will be specified by muscular strength, assuming that the task and intentions of the participant remain unchanged. Therefore, an increase in muscular strength may force the participant to adopt a new co-ordination pattern that would be appropriate to achieve the task, given the new physical constraints of the motor system. However, the likelihood of a co-ordination change will be dependent upon the scale change of the control parameter; that is, the magnitude of the gain in strength will determine the search for a new and appropriate co-ordinative structure, and therefore the emergence of a new co-ordination pattern.

This interrelationship between muscular strength and movement co-ordination has not always been identified. Using regression analysis researchers have reported that muscular strength and intralimb co-ordination contribute significantly but independently to performance during a vertical jump (Tomioka, Owings & Grabiner, 2001). As such, changes in performance could occur by alterations in strength independent of changes in co-ordination. This remains tenable when strength is considered a control parameter because the influence of a control parameter on the order parameter is dependent upon the change in scale of the control parameter (Clark, 1995; Handford et al., 1997). Therefore, the relationship between strength and co-ordination depends upon the magnitude of the strength changes. For example, small gains in strength that are below a critical value may not demand a change in co-ordination of the movement. In simulation studies of multi-joint movements it has been shown that the non-linear properties of the muscles (force-length-velocity relationships) provide a mechanism for adapting to perturbations acting on the movement system (Gerritsen et al., 1998; Van Soest & Bobbert, 1993). Because of these mechanical properties, small perturbations can be accommodated into the co-ordinative structure without the need to develop a new co-ordination pattern. If however the control parameter is scaled beyond a critical value, then the co-ordination pattern is likely to be reorganised to accommodate the new system parameters in order to achieve the task. Such a reorganisation will be manifest in a qualitative change in the order parameter. Therefore, a large increase in strength is likely to require the formation of a new co-ordination pattern to satisfy the constraints of the movement task. In this way, muscular strength and co-ordination cannot be considered to be independent.

A period of exploration may be required to allow the motor system to select an appropriate pattern of co-ordination (formation of new co-ordinative structure) to satisfy the task demands given the change in physical constraints. The exploratory period may be manifested as an increase in the variability of the co-ordination pattern or a change in the frequency composition of the movement trajectories. Combining resistance training with sprint training may expedite the exploratory process, allowing the emergence of a new, more appropriate co-ordination pattern. However, during the period of exploration performance may not be improved. This could explain why previous research investigating the effects of resistance training only has failed to show consistent improvements in accelerative performance immediately following the training period.

### 2.53 Summary

The co-ordination patterns adopted during multi-joint movements are specified, in part, by the physical characteristics of the performer. Included in the physical characteristics is muscular strength which can be considered as a control parameter that can cause a reorganisation of the co-ordination pattern for a given movement. A period of resistance training may force the motor system to change the co-ordination pattern during the sprint performance to one that is appropriate to the change in the control parameter (increased muscular strength). Such a change in co-ordination would be revealed in phase-plane diagrams and RP measures of the sprint movement. However, both the likelihood of a change in co-ordination and the magnitude of the change are likely to be dependent upon the magnitude of the change in muscular strength. An increase in variability or a change in the frequency composition of the kinematic signals associated with the sprint movement may be evident during this period, indicating an exploratory period for the motor system. As such, sprint time may not be improved immediately following a period of resistance training as an appropriate pattern of co-ordination is sought. Resistance training may improve the capacity of the motor system to perform the movement (accelerative sprinting) but it may not provide the appropriate information required to immediately optimise the movement. If the motor system is unable to adapt to the change in strength immediately following the training period and sprint times are not improved, then strategies could be developed to expedite the adaptations in co-ordination to allow the optimisation of the sprinting movement in relation to the increased strength capabilities.

## 2.6 Summary of the review of literature

Sprint velocity is a product of stride length and stride frequency, both of which have many determinants. Stride length and stride frequency are influenced by the GRI during each stance period, with an increase in the horizontal velocity of the CoM at toe-off highlighted as an effective strategy to improve performance. However, the vertical velocity of the CoM at toe-off has been identified as a source of negative interaction between stride length and stride frequency. During early acceleration there is a need for high force under low velocity conditions to overcome the inertia of the body. As the athlete progresses through the acceleration phase there is a greater requirement for the production of force during high velocity movements. Although the forces during stance are primarily generated by the leg extensors, the action of the swinging leg and the arms could influence the magnitude of the forces. Similarly, the starting position appears to influence the performance during the acceleration phase of sprinting. The mono-articular leg extensor muscles perform positive work during each stance period to accelerate the CoM, while the bi-articular leg muscles transfer power between the joints in a proximal-to-distal manner. The bi-articular leg muscles are also responsible for controlling the orientation of the GRF with respect to the CoM, which has been identified as a specific constraint during the stance periods of accelerative sprinting. A rotation-extension strategy allows the production of long strides at high stride frequencies. However, the complexity of the sequencing of muscle activations that optimise the power flow between joints and the direction and magnitude of force may prevent the utilisation of increased strength to improve accelerative sprinting performance.

Muscular strength has been identified as an important component for successful performance during accelerative sprinting. The mechanical expression of muscular strength depends upon the complex interaction of phenotypic and neural factors that are influenced by the stimulus of resistance training. The design of the resistance training programme and the training status of the athlete have a significant effect on the gains in strength. The neuromuscular adaptations associated with a period of resistance training appear to optimise only the practiced movements and not other movements in which the neuromuscular elements are involved. The magnitude of the strength gains may influence the transfer of strength to untrained performance tasks. Studies investigating the effect of resistance training on accelerative sprint performance have provided little evidence supporting a consistent improvement in sprint performance. Few studies have considered issues of familiarisation and reliability associated with the measures of sprint performance. Similarly, simple outcome measures are used to assess sprinting performance with little attention given to the



processes associated with the sprinting movement that may be affected by a resistance training intervention, such as co-ordination.

The co-ordination patterns adopted during multi-joint movements are specified by the confluence of constraints associated with the task, the environment and the physical characteristics of the performer. Muscular strength has been identified as a physical constraint influencing patterns of multi-joint co-ordination. Specifically, muscular strength can be viewed as a control parameter which, if scaled accordingly will cause a re-organisation of the co-ordination pattern in order to satisfy the task. This re-organisation will be revealed in a change in an appropriately selected order parameter such as phase-plane diagrams and the intra and interlimb RP measures. The requirement for the development of a new co-ordination pattern is likely to be dependent upon the magnitude of the change in muscular strength, with small changes requiring a simple re-scaling of the original pattern. However, increases in the variability of the co-ordination pattern or a change in the frequency composition of the kinematic signals associated with the movement immediately following the training period may signify the motor system exploring possible movement solutions to satisfy the demands of the sprinting task.

The research questions for this thesis are:

1. Does a period of resistance training in the absence of concurrent sprint training decrease accelerative sprint time immediately after the training period?

*Predictions from the literature:* The literature investigating the effect of resistance training on accelerative sprinting provides mixed findings. Few studies examining the effects of resistance training in the absence of concurrent sprint training have reported improvements in accelerative sprint time. Therefore, a decrease in accelerative sprint time may not be expected following a resistance training intervention.

2. Does a period of resistance training in the absence of concurrent sprint training cause a change in the co-ordination of movement during accelerative sprinting immediately after the training period?

*Predictions from the literature:* From a dynamical systems perspective of multi-joint co-ordination, muscular strength can be considered a physical constraint that specifies the co-ordination pattern during accelerative sprinting. Therefore, a change in the co-ordination of

the movement during accelerative sprinting immediately after the training period may be expected.

3. Can the changes in sprint time and the co-ordination of movement as a result of resistance training be predicted from the magnitude of the gains in strength?

*Predictions from the literature:* Large correlations between measures of muscular strength and measures of accelerative sprint performance exist in the literature. From a dynamical systems perspective of multi-joint co-ordination an increase in muscular strength, if scaled accordingly will cause a re-organisation of the co-ordination pattern in order to satisfy the task. Therefore, it is expected that the changes in sprint time and the co-ordination of movement as a result of resistance training can be predicted from the magnitude of the gains in strength.



### 3. METHOD

#### 3.1 Participants

Twenty-one male sport science students from the University of Edinburgh volunteered to participate in the study. All participants completed an informed consent form in accordance with the American College of Sports Medicine (Kerney, 1995. Appendix A1.1) and ethical approval for the study was granted by the University of Edinburgh School of Education Ethics Sub-Committee. Participants were randomly assigned to an experimental and a control group prior to training with 11 participants in the experimental group and 10 participants in the control group. The participants were recreationally active, being involved in sports including rugby, soccer and basketball. All had previous experience of resistance training, although none had been involved in a programme of resistance training in the 3-months prior to the study.

Only those who attended all of the training sessions were included in the study, and all participants were required to forego any formal sprint training during the study. The members of the control group were requested to refrain from any resistance or sprint training for the duration of the study. Of the original 21, 4 participants withdrew from the study for reasons unrelated to the study. This left an experimental group of 10 and a control group of 7. The subsequent statistical power using these group sizes with a two-way analysis of variance (ANOVA) design (see Section 3.5) was calculated at 0.50 <sup>1</sup>. The pre-training age, height and mass of the participants are shown in Table 3.1.

**Table 3.1** Pre-training group means for age, height and mass. Values are means  $\pm$  standard deviations.

Group	Age (years)	Height (m)	Mass (kg)
Experimental	18.9 $\pm$ 1.7	1.80 $\pm$ 0.10	79.6 $\pm$ 15.0
Control	21.3 $\pm$ 5.2	1.83 $\pm$ 0.05	80.7 $\pm$ 9.5

The mean pre-training values for normalised maximum strength, explosive strength and 10 m and 20 m sprint times for the experimental and control groups are shown in Table 3.2. Independent t-tests revealed that there were no significant differences between the experimental and control groups on the measures of normalised maximum strength, explosive strength or sprint times prior to the training period ( $P > 0.05$ ).

<sup>1</sup> The method of Campbell & Thompson (2002) was used to calculate statistical power. For the calculation:  $F(1, 15) = 4.58$  which provided  $P = 0.049$ .

**Table 3.2** Pre-training group means ( $\pm$  standard deviation) for normalised maximum strength, explosive strength and 10 m and 20 m sprint times.

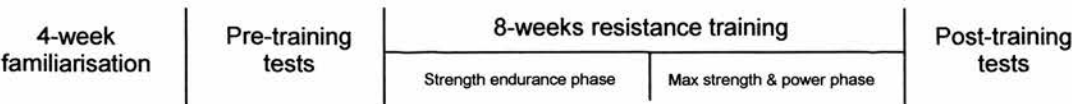
Assessment measure	Group		Group differences			<i>P</i> value*
	Experimental	Control	Difference	Lower 95% CL	Upper 95% CL	
1-RM squat (kg.bm <sup>-3/4</sup> )	6.08 $\pm$ 0.77	5.61 $\pm$ 0.96	0.47	-0.42	1.37	0.275
UL PP (W)	4096 $\pm$ 789	3916 $\pm$ 557	180	-561	921	0.613
30% 1-RM PP (W)	3680 $\pm$ 716	3512 $\pm$ 623	168	-547	883	0.624
60% 1-RM PP (W)	3324 $\pm$ 788	3094 $\pm$ 423	230	-470	930	0.495
10 m time (s)	1.84 $\pm$ 0.13	1.91 $\pm$ 0.11	-0.07	-0.20	0.06	0.252
20 m time (s)	3.21 $\pm$ 0.17	3.30 $\pm$ 0.21	-0.10	-0.30	0.09	0.259

Note: \* 15 degrees of freedom. CL = confidence limit of the difference; 1-RM = one repetition maximum; kg.bm<sup>-3/4</sup> = kilogram load per kilogram body mass to power 3/4 (see Section 3.45); UL = unloaded vertical static jump; PP = peak power output.

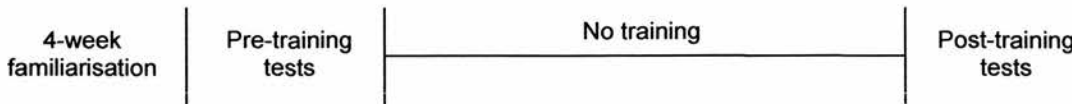
### 3.2 Study design

A randomised controlled design was used to investigate the effects of resistance training on the sprint time and co-ordination pattern associated with the acceleration phase of sprint running. An experimental group followed an 8-week periodised resistance training programme, while a control group participated in the testing sessions only. Testing was performed on two separate occasions, pre-training and post-training (Figure 3.1). This design provided all of the data necessary to answer the 3 research questions of the thesis.

Experimental group:



Control group:



Time

**Figure 3.1** Schematic representation of the study design.

### 3.3 Training programme

The resistance training programme combined heavy and light sessions similar to those used by Harris et al. (2000). The programme consisted of 2 microcycles of 4-weeks in length, with strength endurance emphasised in the first while the second emphasised the development of maximum strength and power. The volumes and loads used in each microcycle were as follows: microcycle 1 comprised 4-weeks of 3 x 12 repetitions at 12-repetition maximum (RM); microcycle 2 comprised 4-weeks of 3 x 5 repetitions at 5-RM. The training programme is described in detail in Appendix A1.2.

Major and assistance exercises were included in the training programme (Tables 3.3 & 3.4). Major exercises are multi-joint movements involving the major muscle groups, while assistance exercises are single-joint movements that train smaller muscle groups (Kraemer, 2002). The exercises used were typical of those recommended in sprint-training articles (e.g. Dintiman et al., 1998; Sheppard, 2003; Young et al., 2001). All participants completed a 4-week familiarisation period prior to their assignment to the experimental and control groups to counter the possibility of learning mechanisms contributing significantly to any gains in strength (Jones & Rutherford, 1987). During this period, the participants performed all of the training and testing exercises. This period was also used to find the experimental participants' 12-RM for each of the training exercises to be used in the strength endurance microcycle.

**Table 3.3** Outline of the exercises used in the strength endurance microcycle of the resistance training programme.

Exercise	Day	Sets	Repetitions	Target RM	
Parallel squats	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Bench-press	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Push-press	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Flys	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Sit-ups	M & Fr	3	15 - 25	–	–
Power cleans	We	3	12	12-RM – 10% (We)	
SLDL	We	3	12	12-RM – 10% (We)	
CGSS	We	3	12	12-RM – 10% (We)	
THE	We	3	15 - 25	–	

Note: M = Monday (heavy); We = Wednesday (moderate); Fr = Friday (light); RM = repetition maximum; SLDL = stiff-legged deadlift; CGSS = clean grip shoulder shrugs; THE = trunk hyperextensions.

**Table 3.4** Outline of the exercises used in the maximum strength and power microcycle of the resistance training programme.

Exercise	Day	Sets	Repetitions	Target RM	
Parallel squats	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
Bench-press	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
Push-press	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
Flys	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
SU (5 – 10 kg)	M & Fr	3	10 - 15	–	–
Power cleans	We	3	5	5-RM – 10% (We)	
SLDL	We	3	5	5-RM – 10% (We)	
CGSS	We	3	5	5-RM – 10% (We)	
THE (5 – 10 kg)	We	3	10 - 15	–	

Note: M = Monday (heavy); We = Wednesday (moderate); Fr = Friday (light); RM = repetition maximum; SU = sit-ups; SLDL = stiff-legged deadlift; CGSS = clean grip shoulder shrugs; THE = trunk hyperextensions.

Training loads during each microcycle were determined using a target RM as recommended by Kraemer (2002). The loads were increased by 5% to 10% in consecutive weeks during the first 3-weeks of each cycle, with a reduction in load during the final week. Training frequency was 3-times per week, incorporating heavy (Monday), moderate (Wednesday) and light (Friday) training days to reduce the risk of overtraining (Stone et al., 2000). Variations in the loads were achieved by reducing the target RM by 10% on moderate days and 20% on light days. This variation produced a training regime that combined high force and high velocity movements (Cronin et al., 2002; Stone, 1993). As well as the variations in volume and load, exercises were varied to reduce the risk of overtraining. Exercises performed on the medium days were different from those performed on the heavy and light days (Tables 3.3 & 3.4).

The rest periods between exercise sets during each training session were 2-minutes during the strength endurance phase and 3-minutes during the maximum strength and power phase (Kraemer, 2002). Each training session was supervised by an instructor to ensure that participants adhered to the programme and that the appropriate safety factors were applied (e.g. spotting of the participants). Prior to each training session, a standardised warm-up was performed by each participant consisting of a period of 5-minutes of jogging, followed by various dynamic stretches (Appendix A1.3).

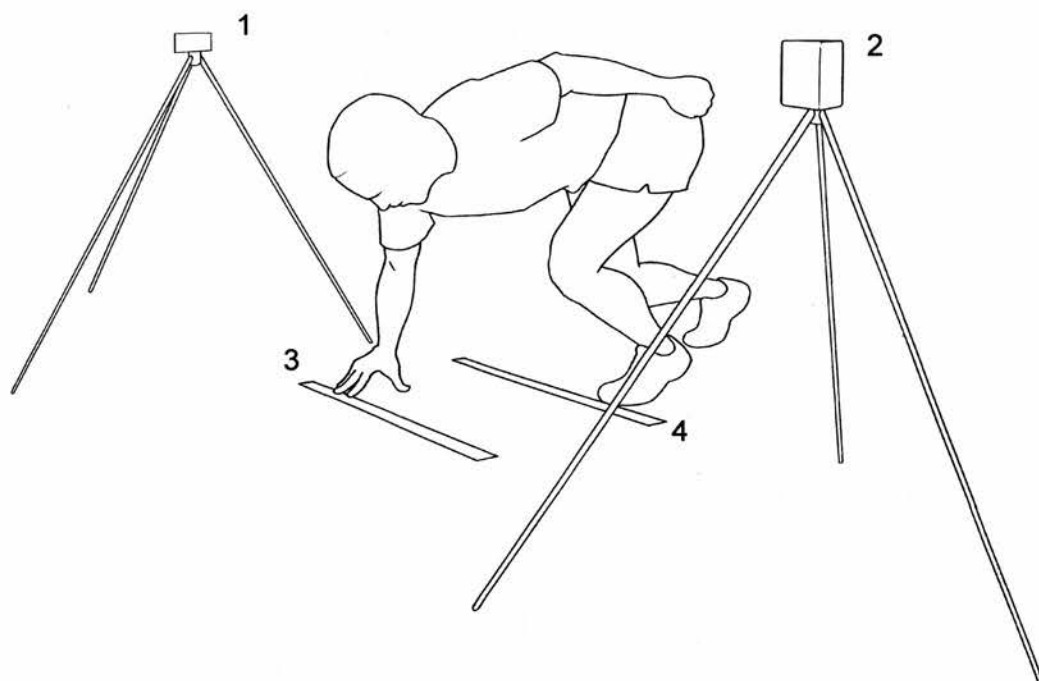
### **3.4 Assessment measures**

The assessment measures were administered pre and post-training (Figure 3.1). The measures were sprint time and kinematic variables, maximum strength, explosive strength and anthropometric measures (height, weight, percent body fat). Each of the 2 testing sessions (pre and post-training) was performed over a week-long period, with the assessments following the same order each time: 1. Maximum strength (Day 1) 2. Anthropometric measures (Day 2) 3. Sprint time and kinematic variables (Day 4) 4. Explosive strength (Day 5). All testing was performed at the same time of the day for each participant.

#### **3.4.1 Sprint time and kinematic variables**

Sprint time was assessed using a 20 m straight-line sprint from a 3-point, crouched stationary start (Figure 3.2). This starting position was chosen in an attempt to constrain the participant's posture as this can influence the sprint performance (Schot & Knutzen, 1992). The time over the first 10 m in addition to the 20 m time was recorded. The times for these 2 distances were recorded using telemetric photocells (Sprint Timer Telemetry, Cranlea & Company, England) which were placed at the 0, 10 m and 20 m marks of an indoor running track. The first pair of photocells were set at a height of 0.85 m, while the other 2 pairs were at a height of 1 m. The participants began each sprint from a line marked 0.5 m behind the start line to avoid breaking the beam of the first photocells before the sprint was started. Each participant performed 3 runs of maximal effort, with the mean 10 m and 20 m sprint times used in the subsequent analysis.

The sprints were initiated by the participants when they were ready and 3-minutes recovery was provided between the runs. Prior to the sprints, the participants performed a standardised warm-up consisting of jogging, followed by specific static exercises, dynamic exercises and sprint drills (Appendix A1.3). Using this protocol it was found that the sprint times across 3 testing sessions did not differ significantly, and so familiarisation sessions were not required to obtain a reliable measure of sprint time (Moir & Glaister, 2004). However, all of the participants in the training study performed a practice session during the 4-week familiarisation period to ensure that they were starting from their preferred foot. The coefficients of variation (CV) and intraclass correlation coefficients (ICC) for the 10 m and 20 m sprint times are shown in Table 3.5 (Moir & Glaister, 2004). These data show that the 10 m and 20 m times demonstrate high test-retest reliability and small within-individual variation.



**Figure 3.2** The crouch start during the 20 m sprint. Note: 1 = photocell reflector; 2 = transmitter/receiver photocell; 3 = start line; 4 = 0.5 m mark.

**Table 3.5** Coefficients of variation, intraclass correlation coefficients and associated 95% confidence limits for the 10 m and 20 m sprint times.

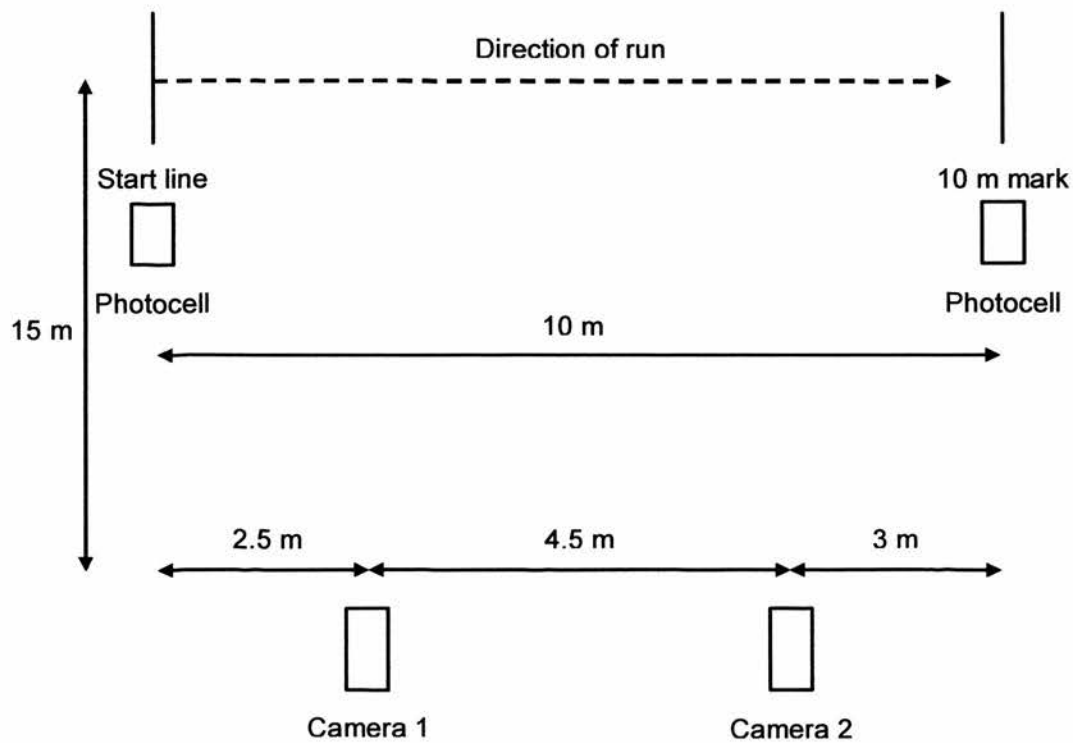
Sprint	CV (%)	95% confidence limits		ICC	95% confidence limits	
		Lower	Upper		Lower	Upper
10 m	1.6	1.1	2.1	0.90	0.75	0.97
20 m	1.5	1.0	2.0	0.87	0.68	0.96

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient.

Sprint performance over the first 10 m of each 20 m trial was recorded using 2 stationary digital cameras (JVC, GR-DVL 9800, Japan) with sampling frequencies of 120 Hz. The cameras were set at a height of 0.85 m and were positioned 4.5 m apart and 15 m from the line of the sprint (Figure 3.3). Camera 1 covered an area of approximately 7.5 m x 3 m, while camera 2 covered an area of approximately 6 m x 3 m. No phase-locking was required with this configuration as camera 1 recorded the first 2 strides of the sprint and camera 2 recorded the third stride for each participant. The axes of the cameras were perpendicular to the plane of motion of the participants during the sprint. Both camera views were calibrated



using metal frames of known dimensions. The video footage provided 2-dimensional kinematic data for the first 3 strides of the 20 m sprint for each participant.



**Figure 3.3** Plan showing the camera positions relative to the line of running during the first 10 m of the 20 m sprint.

Each stride was digitised using APAS software (Ariel Performance Analysis System, version 1.0, Ariel Dynamics). A 7-segment model of one side of the body was constructed for each participant. The segments included the combined trunk-head-neck, upper arm, forearm, hand, thigh, shank and foot using the definitions of Winter (1979) as shown in Table 3.6. The segment characteristics shown were used to calculate the position of the body centre of mass (CoM) using the APAS software. The participants wore a white lycra body suit and joint centres were marked with squares of black tape (approximate size 3 cm x 3 cm). The locations of the joint centres were identified using the protocol suggested by Plagenhoef (1971). The trials were digitised using the automatic function of the APAS software.

3.42 Processing of kinematic variables

A stride cycle was defined as the period between toe-off and the next ipsilateral toe-off. Toe-off was determined from the raw data as the point at which the vertical displacement of the 5<sup>th</sup> metatarsal phalangeal joint (MPJ) increased from its position during the stance period of

the stride cycle (when the foot was in contact with the ground). The selected kinematic variables were calculated by a Fortran programme (coded by Sanders, 2004. Figure 3.4). The raw x and y co-ordinates for each joint were filtered using a second order, dual pass, recursive Butterworth digital filter with a 7 Hz cut-off frequency. The co-ordinates were filtered to at least 15 frames before and beyond each stride cycle so that the derivatives of the positional data would not be distorted following the filtering procedure (Vaughan, 1982). The cut-off frequency was selected by using harmonic analysis and the method outlined by Yu et al. (1999) (see Appendix A1.4 for discussion).

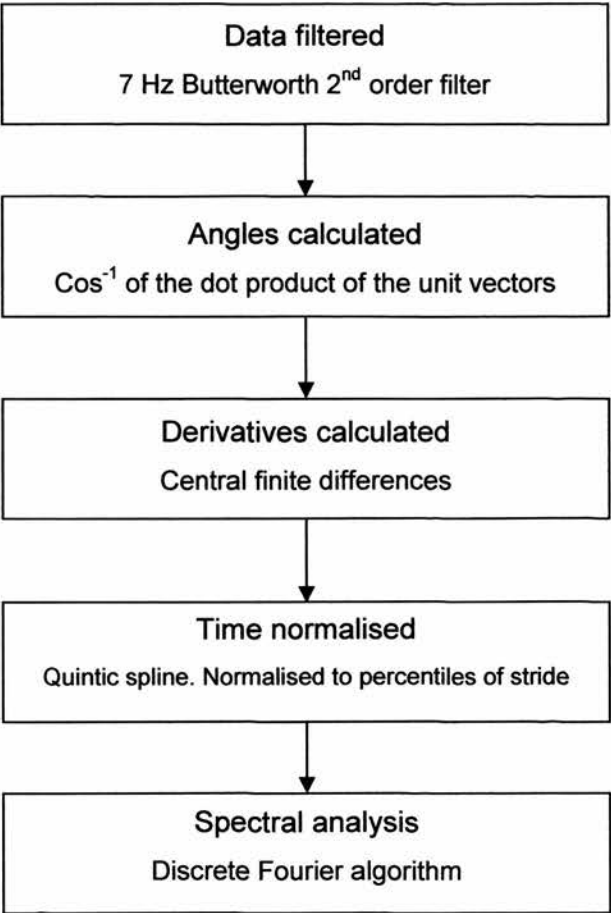
**Table 3.6** Anthropometric data used in the digitised 7-segment model.\*

Segment	Definition	Seg wt/ body wt	Centre of mass/ Segment length		Radius of gyration/ Segment length		
			Proximal	Distal	CoG	Proximal	Distal
Trunk-head- neck	Glenohumeral axis/ Greater trochanter	0.578	0.660	0.340	0.503	0.830	0.607
Upper arm	Glenohumeral axis/ Elbow axis	0.220	0.682	0.318	0.468	0.827	0.565
Forearm	Elbow axis/ Ulnar styloid	0.016	0.430	0.570	0.303	0.526	0.647
Hand	Wrist axis/ 2 <sup>nd</sup> knuckle	0.006	0.506	0.494	0.297	0.587	0.577
Thigh	Greater trochanter/ Femoral condyle	0.100	0.433	0.567	0.323	0.540	0.653
Shank	Femoral condyle/ Lateral malleolus	0.465	0.433	0.567	0.302	0.528	0.643
Foot	Lateral malleolus/ 5 <sup>th</sup> MPJ	0.0145	0.500	0.500	0.475	0.690	0.690

Note: \* Data from Winter (1979) pp.151-152; CoG = centre of gravity; MPJ = Metatarsal phalangeal joint.

Following filtering joint angles were calculated using the  $\cos^{-1}$  of the dot product of the unit vectors of adjoining body segments. Angles greater than  $180^\circ$  were corrected to  $360^\circ$  minus the calculated angle. Occurrences of a joint moving from  $< 180^\circ$  to  $> 180^\circ$  (and  $> 180^\circ$  to  $< 180^\circ$ ) were identified as discontinuities in the second derivative (angular acceleration) of the uncorrected data. The time derivatives of the positional data were calculated for each joint using central finite differences. The first and second time derivatives (velocity and acceleration, respectively) were calculated for each cycle. The data were then time normalised to 101 data points using a quintic spline procedure, yielding data corresponding to percentiles of each stride. This allowed direct comparisons between strides recorded during the pre and post-training testing sessions and so individual changes in co-ordination

could be assessed. A discrete Fourier algorithm was used to calculate the power spectrum of the angular displacement signal for each joint.



**Figure 3.4** Flow chart showing the procedures for the analysis of kinematic variables during a stride cycle.

3.421 Effect of digitising errors on calculation of kinematic variables

The errors associated with the digitising process were assessed by manually digitising a single stride cycle 5 times following data filtering. A detailed description appears in Appendix A1.5. The root mean square error (RMSE) was then calculated for the position data and the time derivatives of the joints and also the continuous relative phase (CRP) measures (see Appendix A1.5 for discussion). These data were compared to the RMSE calculated across all participants from the pre-training testing session. The RMSE data for the joint angular displacements and derivatives are shown in Table 3.7, with the RMSE for the CRP measures in Table 3.8.

**Table 3.7** Root mean square error for the joint kinematic variables calculated across 5 repeat-digitised trials and the mean data from the pre-training testing session. In all cases, stride 2 was analysed.

Kinematic variable	Joint							
	Shoulder		Hip		Knee		Ankle	
	Digitised	Pre-training	Digitised	Pre-training	Digitised	Pre-training	Digitised	Pre-training
Displacement (degrees)	1.01	7.14	0.87	4.24	0.67	4.89	1.64	3.58
Velocity (degrees.s <sup>-1</sup> )	36.47	83.16	22.05	57.88	17.25	82.26	36.69	65.78
Acceleration (degrees.s <sup>-2</sup> )	1234.06	2492.44	933.07	1800.16	710.26	2277.72	1628.83	2549.24

**Table 3.8** Root mean square error for the continuous relative phase couplings calculated across 5 repeat-digitised trials and the mean data from the pre-training testing session. In all cases stride 2 was analysed.

	Continuous relative phase coupling		
	Shoulder-hip (degrees)	Hip-knee (degrees)	Knee-ankle (degrees)
	RMSE	RMSE	RMSE
Digitised	4.73	3.04	6.12
Pre-training	11.18	9.91	12.74

Note: RMSE = root mean square error.

For all of the variables assessed, the digitising errors in the calculation of the kinematic variables were less than the within-individual variation during the pre-training testing session. Therefore, digitising error could be rejected as a factor causing substantial differences between the pre and post-training data or in preventing differences reaching statistical significance.

### 3.43 Selection of kinematic and kinetic variables for analysis

To investigate the factors contributing to a change in sprint performance following a period of resistance training, and so contribute to answering the research questions, the following kinematic and kinetic variables were selected:

#### *Stride length and stride frequency*

As sprint running is the product of stride length and stride frequency these variables were expected to be sensitive to any changes in sprint performance. An increase in stride length may reflect an increase in the force produced during the stance period of each stride. It has been shown that faster sprinters have higher stride frequencies during the acceleration phase (Murphy et al., 2003), and so a change in stride frequency might be expected if sprint performance is changed.

#### *Flight and stance times*

As the time taken to complete one stride includes the flight and stance periods, these variables are related to stride frequency. Analysing flight and stance time provides further information about the nature of the transfer of strength from the resistance training intervention to the sprinting task. Increases in the flight times for each stride indicate an increase in the impulse due to the vertical component of the GRF produced during each stance period. A shorter stance period may reflect an increase in explosive strength as a

result of resistance training because less time is required to generate the force necessary to accelerate the body CoM. It has been shown that faster athletes have shorter stance periods than their slower counterparts during the acceleration phase (Murphy et al., 2003).

#### *Impulse acting on the body centre of mass*

Impulse is a measure of the effect of a force during the time that it acts (Zatsiorsky, 2002). Assessing the linear impulse acting to change the motion of the CoM provides further information about the transfer of strength from the resistance training intervention to the sprint performance. For example, an increase in strength due to the resistance training exercises could increase the vertical forces during sprinting which would indicate a transfer, albeit one that may not be beneficial to accelerative sprinting. An increase in vertical force may increase the net vertical impulse leading to increased vertical velocity of the CoM at toe-off and, concomitantly, an increased flight time. This may reduce performance because it has been shown that slower sprinters have greater vertical velocities of the CoM at the end of the stance periods during the accelerative sprinting (Čoh et al., 2000).

#### *Joint angles at touch-down and toe-off*

Changes in co-ordination during late flight could affect the generation of force early during stance (Wood, 1987). The analysis of the joint angles at touch-down would provide information about possible changes in co-ordination during this time. It has been shown that toe-off occurs with less extension at the knee and hip joints in faster athletes (Mann & Herman, 1985; Murphy et al., 2003). However, following a resistance training intervention an increase in hip and knee extension at toe-off may be expected given that the training exercises (e.g. squat, cleans) emphasise extension torques about these joints.

#### *Joint ranges of motion*

The range of motion about each joint was measured to provide information about the change of co-ordination at individual joints. For example, the temporal organisation at each joint may be maintained following an increase in strength as a result of the resistance training intervention, but the co-ordination pattern may be re-scaled with greater displacement. The greater displacement may occur due to force being applied through a greater range following the resistance training intervention.



### *Phase-plane diagrams*

Phase-plane diagrams plot the angular velocity of a joint as a function of joint angular position, and so provide spatial information across the entire stride cycle. Modifications in the shape of the diagram trajectory reflect a change in behaviour of the motor system. Because the action of the arms may be important in accelerative sprinting, phase-plane diagrams of the shoulder joint in addition to the lower limb joints would provide useful information about the changes in co-ordination following a period of resistance training.

### *Relative phase*

Relative phase (RP) reflects inter-joint phase relations at particular times during a movement. Continuous relative phase (CRP) represents the inter-joint phase relations across an entire movement cycle. In the present study the hip-knee and knee-ankle joint couplings would be expected to be influenced by the resistance training stimulus, given the nature of the training exercises. The shoulder-hip joint coupling may also influence the sprint performance during the acceleration phase of sprinting. Modifications in the RP relationships represent new behaviours of the motor system. As well as the overall shape of the graphs, the variability of the CRP measures provides useful information about the state of the motor system and its readiness to change co-ordination patterns following an increase in muscular strength.

### *Spectral analysis*

Spectral analysis was used to show a change in the frequency composition of the joint angular displacement signals. A change in the frequency composition of the joint angular displacement signal following a period of resistance training may indicate the motor system exploring possible movement solutions given a change in the physical constraints of the system. Similarly, a shift towards higher frequency components in the joint data may reflect a reliance on information from higher derivatives in the execution of the sprint movement following the resistance training intervention.

### 3.44 Calculation of variables

A stride cycle was defined as the period between toe-off and the next ipsilateral toe-off. Toe-off was determined from the raw data as the point at which the vertical displacement of the 5<sup>th</sup> MPJ increased following the stance period of the stride cycle. For each participant the following variables were calculated for each stride cycle during the 3 sprint trials performed

pre and post-training (the mean of each variable calculated across 3 sprint trials was used in the analysis):

#### *Stride length*

Stride length was defined as the horizontal displacement (metres) between consecutive ipsilateral toe-off events. It was calculated as the difference between the scaled x co-ordinates of the 5<sup>th</sup> MPJ at the frames prior to toe-off. Toe-off was calculated as the frame corresponding to the point at which the vertical displacement of the 5<sup>th</sup> MPJ increased from the position during stance.

#### *Stride frequency*

Stride frequency (Hertz) was calculated as the inverse of the time taken to complete one stride cycle.

#### *Flight time*

The time (seconds) between consecutive ipsilateral stance periods defined the flight time. Flight time began at the frame corresponding to the point when the scaled y co-ordinates of the 5<sup>th</sup> MPJ exceeded the minimum values during each stride cycle (the stance period). The flight time ended at the frame prior to that corresponding to when the scaled y co-ordinates of the 5<sup>th</sup> MPJ achieved the lowest values during the stride (next ipsilateral stance period).

#### *Stance time*

The time (seconds) that each ipsilateral foot was in contact with the ground defined stance time. Touch-down occurred at the frame corresponding to the point when the scaled y co-ordinates for the 5<sup>th</sup> MPJ marker reached their minima during each stride cycle. The frame prior to that corresponding to the point when the scaled y co-ordinates exceeded the lowest point (when the 5<sup>th</sup> MPJ was deemed to have left the ground) marked the end of the stance period.

#### *Impulse acting on the body centre of mass*

The mean vertical and horizontal impulse (N.s) acting during the stance period was calculated for each stride across the 3 trials pre and post-training. Linear impulse equals the increment in linear momentum, and was calculated as follows in both the vertical and horizontal directions:

$$I = mv_2 - mv_1$$

where  $I$  = the linear impulse,  $m$  = the mass of the participant,  $v_1$  = the velocity of the CoM at the beginning of the stance period,  $v_2$  = the CoM velocity at the end of the stance period. Calculated in this way, the vertical impulse represents the net impulse as the impulse due to the reaction to the gravity force is not included.

#### *Joint angles at touch-down and toe-off*

The angles (degrees) at the shoulder, hip, knee and ankle joints at the frame corresponding to touch-down and toe-off defined these joint angles.

#### *Joint ranges of motion*

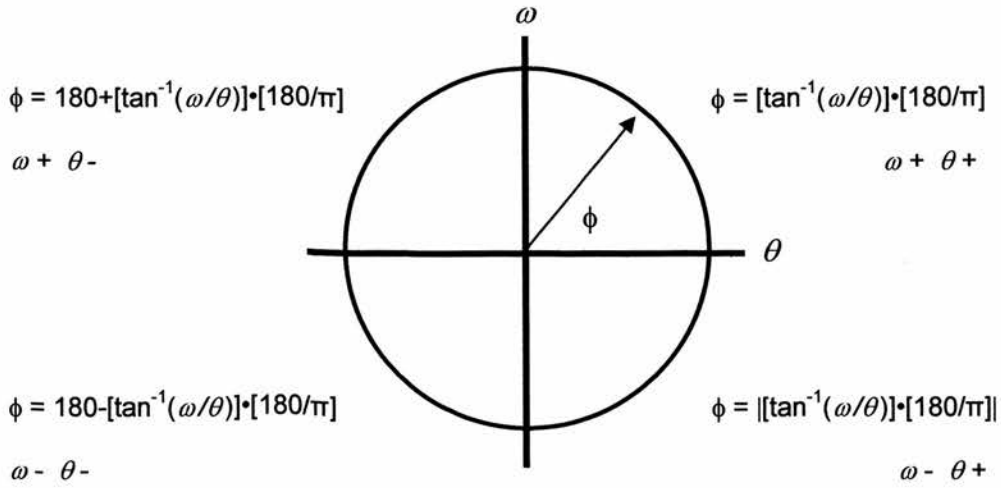
The difference between the maximum and minimum angles (degrees) about the shoulder, hip, knee and ankle joints during each stride cycle defined the joint ranges of motion.

#### *Phase- plane diagrams*

Phase-plane diagrams were constructed using the angular displacement and angular velocity for each joint (shoulder, hip, knee and ankle). The diagrams were constructed with the lower derivative on the horizontal axis and the higher derivative on the vertical axis. Data from the mean of 3 trials pre and post-training was used to construct the phase-plane diagrams for each participant during the 3 stride cycles. Mean diagrams for the groups were then constructed. The angle of the mean direction of the data points for the phase-plane diagrams for each participant was calculated using methods from circular statistics (see 3.5 Statistical analyses). Correlations were performed on the phase angle ( $\phi$ ) calculated for the mean phase-plane diagrams for each participant pre and post-training to assess the association. The  $\phi$  at each percentile of the stride cycle was calculated as follows:

$$\phi = \tan^{-1} \omega(t) / \theta(t)$$

where  $\omega(t)$  is the angular velocity and  $\theta(t)$  is the angular displacement for each point during the stride cycle. The appropriate phase angle corrections were made for the movement through different phases based on the sign of  $\theta$  and  $\omega$  (Figure 3.5). The pre and post-training differences in the correlation coefficients for  $\phi$  during each stride cycle were then compared to assess the association and therefore highlight any changes in the pattern at each joint.



**Figure 3.5** Phase angle ( $\phi$ ) definition based on a phase-plane diagram of angular displacement ( $\theta$ ) and angular velocity ( $\omega$ ). The corrections for the phase angle during the different phases are shown.

### Relative phase

The RP during each stride cycle was constructed for the shoulder-hip, hip-knee and knee-ankle couplings using the displacement-velocity phase-plane diagrams for the appropriate joints. The angular displacement and angular velocity data were normalised by dividing each point by the absolute mean value during the stride cycle<sup>1</sup>. Following normalisation, the  $\phi$  were calculated using the same method as for the phase-plane diagram (shown above), with appropriate corrections made for the movement through different phases (Figure 3.5).

The RP was defined as the difference between the normalised  $\phi$  of two joints at a particular time during a stride cycle, with the CRP defined as the difference between the normalised  $\phi$  of two joints graphed across an entire stride cycle. For each joint coupling the  $\phi$  of the proximal joint was subtracted from the  $\phi$  of the distal joint as follows:

$$\phi_{\text{relative phase}} = \phi_{\text{distal joint}} - \phi_{\text{proximal joint}}$$

<sup>1</sup> One of the limitations with CRP is the need for amplitude normalisation prior to the calculation of the phase angle, particularly for intra-limb co-ordination, to account for amplitude differences between the oscillators so that one joint/segment does not dominate the calculated CRP (Hamill et al., 2000). The methods typically involve normalising the data to a unit circle (Van Emmerik & Wagenaar, 1996a) or normalising the angular displacement using the maximum (+1) and minimum (-1) values while the angular velocity data is normalised to  $\pm 1$  depending upon where the maximum absolute value occurred (Burgess-Limerick, Abernethy & Neal, 1993). However, these normalisation methods tend to distort the raw data and produce false merging points at the maximum and/or minimum values, depending upon which method is selected. Therefore, information is lost, with the resulting CRP trajectories being affected by the normalisation technique employed (Hamill et al., 2000; Kurz & Stergiou, 2002). Normalising the displacement and velocity data to the mean values across the movement cycle may be an appropriate technique as this is unlikely to produce excessive distortions in the original data, preserving the dynamic behaviour captured in the original phase-plane diagrams.

where  $\phi_{\text{relative phase}}$  = the relative phase angle between the distal and proximal joints,  $\phi_{\text{distal joint}}$  = the phase angle of the distal joint,  $\phi_{\text{proximal joint}}$  = the phase angle of the proximal joint. For the shoulder-hip RP the hip  $\phi$  was subtracted from the shoulder  $\phi$ . A RP of  $0^\circ$  indicates that the joints are in-phase, with a RP of  $180^\circ$  indicating anti-phase behaviour of the joints (Hamill et al., 1999; Peters et al., 2003). Measures of discrete RP for the joint couplings were recorded at toe-off and touch-down during each stride cycle.

For each stride cycle, the participants' mean ensemble graphs were constructed for CRP calculated across the 3 sprint trials performed pre and post-training. The mean ensemble CRP graphs for the groups were then constructed. The CRP graphs were analysed using 3 methods. First, the absolute mean CRP was quantified over the entire stride cycle using the method described by Hamill et al. (1999) and Heiderscheit, Hamill and Van Emmerik (1999). The pre and post-training mean absolute CRP were then compared for each participant. Second, in order to provide detail beyond the absolute mean value, the pre and post-training mean ensemble CRP graphs for each joint coupling were constructed for the experimental and control groups. The 95% confidence intervals of the true mean were then calculated using the following equation:

$$\bar{x}_i \pm t\sigma_{\text{mean}}/\sqrt{n}$$

where  $\bar{x}_i$  = the  $i$ th data point on the mean ensemble graph,  $t$  = the t-statistic,  $\sigma_{\text{mean}}$  = the standard deviation of the mean,  $n$  = the number of participants in the sample (experimental group = 10; control group = 7). The mean post-training curves and 95% confidence intervals of the true mean for the experimental and control groups were then plotted against the respective pre-training curves. A significant difference was deemed to have occurred during a stride cycle at the point where the confidence intervals for the pre and post-training graphs did not overlap. Finally, correlations between the pre and post-training mean ensemble CRP graphs constructed for each participant were calculated to identify the association between the graphs. The pre and post-training correlation coefficients for the groups were compared.

The within-individual variability of the joint couplings was assessed by investigating the variation of the CRP graphs. The variation was quantified using the RMSE calculated over an entire stride cycle using the CRP from the 3 pre and post-training sprint trials for each participant:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^k \left[ \sum_{j=1}^N (a_{ij} - \chi_i)^2 \right]}{k}}$$

where  $N$  = the number of trials (3),  $a_{ij}$  = the  $i$ th point of the  $j$ th trial,  $\chi_i$  = the mean of the  $i$ th point calculated across 3 trials,  $k$  = the number of data points (101).

### *Spectral analysis*

Spectral analysis was performed on the angular displacement signals calculated for the shoulder, hip, knee and ankle joints following data filtering. These signals were represented as a Fourier function comprising 15 harmonics. To ensure that the data set was cyclic in terms of the fundamental frequency each signal was de-trended and demeaned. This produced a signal that had the same start and end value and oscillated around a mean of zero. The Fourier coefficients (cosine and sine terms of the signal) were calculated using the following formula:

$$A_m = \sum_{r=-n}^{n-1} S_r \cdot \cos \frac{2 \cdot \pi \cdot m \cdot r}{N}$$

and

$$B_m = \sum_{r=-n}^{n-1} S_r \cdot \sin \frac{2 \cdot \pi \cdot m \cdot r}{N}$$

where  $A_m$  = amplitude of the cosine function,  $B_m$  = amplitude of the sine function,  $n$  = the number of the data point in sequence,  $S_r$  = the  $r^{\text{th}}$  sample value,  $\pi = 3.1415927$ ,  $m$  = the harmonic number,  $r$  = the number of the sample,  $N$  = the number of data points. The power within each harmonic was calculated using the amplitudes of the Fourier coefficients to produce a power spectrum for each joint:

$$\text{Power within harmonic} = (A_m^2 + B_m^2) \cdot 2$$

The power within each harmonic from the power spectrum was expressed as a percentage of the total power of the signal. The power spectrum for the first 10 harmonics was used in the



analysis. The analysis of the pre-training data revealed that the first 10 harmonics comprised frequencies up to (mean  $\pm$  standard deviation):  $20.89 \pm 1.99$  Hz,  $21.75 \pm 1.73$  Hz and  $21.78 \pm 1.82$  Hz for strides 1, 2 and 3, respectively. The mean power spectrum for each participant calculated from the 3 pre and post-training trials for each stride was used in the analysis for each joint. Mean power spectrums were constructed for the experimental and control groups.

### 3.45 Maximum strength

In order to attribute the changes in sprint performance (research question 1) and co-ordination (research questions 2 & 3) to the effect of the resistance training intervention, changes in strength were assessed. Maximum strength of the lower and upper-body was assessed using free-weights parallel squat and flat bench-press one repetition maximum (1-RM) tests, respectively. These exercises have been shown to be valid indicators of lower and upper-body maximum strength (Jackson, Watkins & Patton, 1980), and have been used extensively in the literature (e.g. Harris et al., 2000; Hickson, Hidaka & Foster, 1994).

The 1-RM tests were performed on the first day of testing and the parallel squat was performed prior to the bench-press. A standardised warm-up consisting of a 5-minute period of jogging was performed by all participants before the first sub-maximal repetitions of the parallel squat test. For both tests a standard 20 kg Olympic barbell and Olympic disks (Eleiko, Sweden) were used. The parallel squat was performed in a squat rack (Panatta, Italy), while a bench (Powersport, UK) was used for the bench-press test. Spotters were employed during each of the exercises to ensure the safety of the participants. The absolute load lifted successfully (measured in kilograms) was recorded as an outcome measure on both tests. From this, the load relative to body mass was calculated. Atkins (2004) reported that strength normalised to the exponent of 1 (per  $\text{kg}^{-1}$ ) penalised heavier athletes and may therefore mask any differences in performance. Accordingly, the equation proposed by Jaric (2002) was used in the present study whereby the absolute load is normalised to the body mass to the power  $2/3$ :

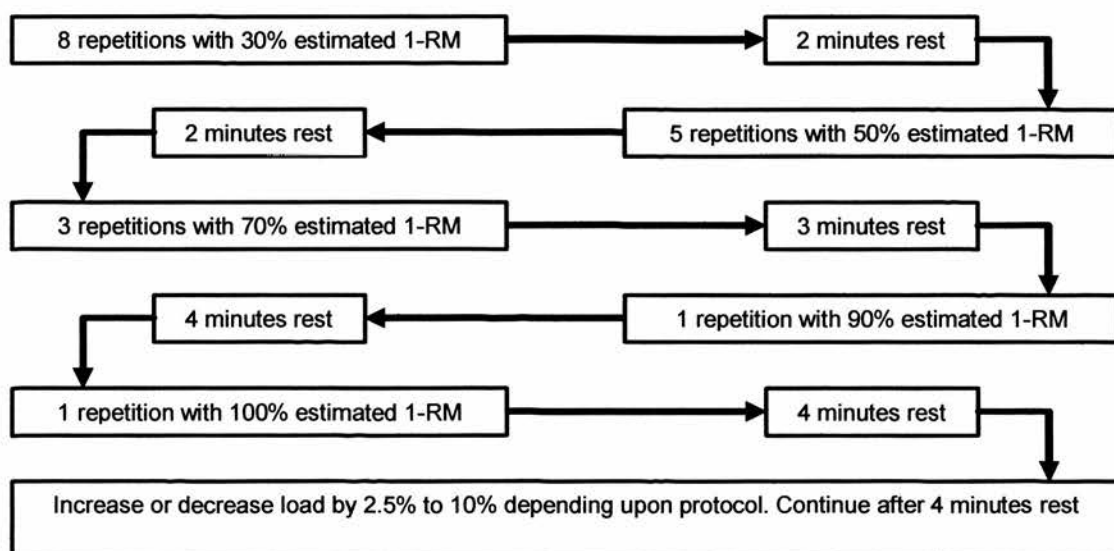
$$S_n = S/m^{-2/3}$$

where  $S_n$  = the normalised strength ( $\text{kg/kg}$  body mass),  $S$  = the load lifted ( $\text{kg}$ ),  $m^{-2/3}$  = the body mass ( $\text{kg}$ ) of the participant to the power two-thirds. The allometric parameter  $2/3$  has been calculated from regression models and accounts for the relationship between muscular

force and body mass (Jaric, 2002). Therefore, this normalisation procedure accounts for role of body size in the assessment of maximum strength.

### 3.451 1-RM parallel squat protocol

The 1-RM testing protocol was based upon that proposed by Baechle, Earle and Wathen (2000). Briefly, during the squat the participant descended to a depth where the tops of the thighs (line from the inguinal fold to the top of the patella) were parallel with the floor. From this position the participant ascended in a continuous movement. Each participant's maximum load was estimated between 1.2 and 1.8 times body mass or taken as advised by the participant. The increments shown in Figure 3.6 were then followed. Following the estimated 1-RM attempt, the load was increased or decreased by 5% to 10% depending upon whether the lift was successful or not. A lift was deemed successful if the top of the thighs were parallel to the ground during the lowest point of the descent and the bar continued to move upward throughout the ascent without assistance. Spotters were used during the squat attempts. A pilot study with physically active males revealed that 1-RM loads were achieved within 5 lifts (mean  $4.4 \pm 1.1$  lifts) from the estimated 1-RM using this protocol. All participants performed parallel squats during the 4-week familiarisation period and so were considered competent in the movement.



**Figure 3.6** The repetitions, loads and rest periods used in the tests of lower and upper-body maximum strength. From: Baechle et al. (2000).

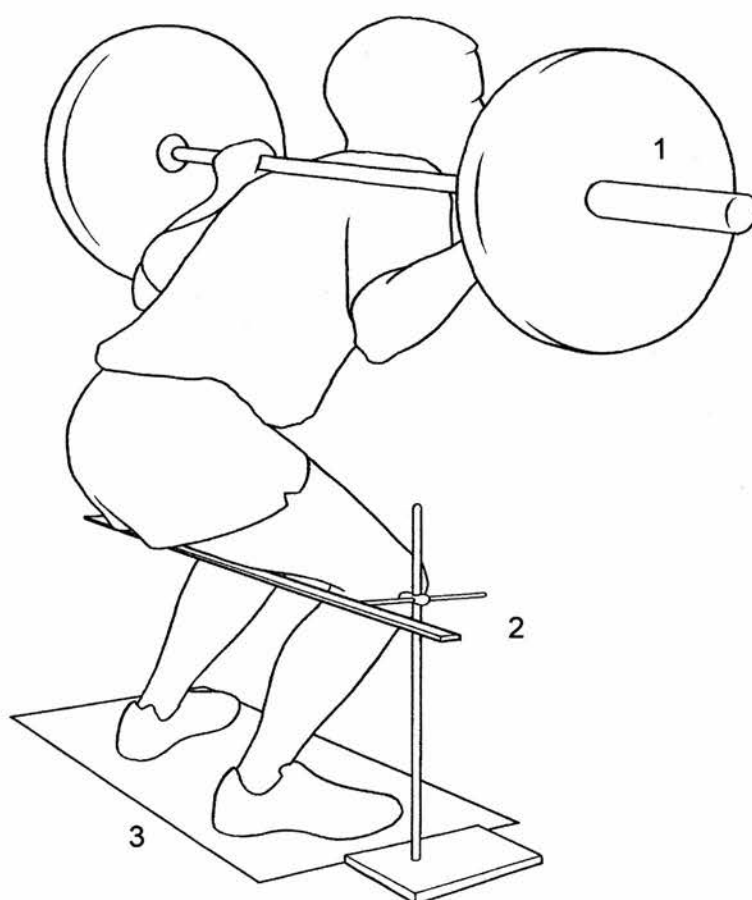
### 3.452 1-RM bench-press protocol

The testing protocol for the 1-RM bench-press was based upon that used by Baechle et al. (2000). During the bench-press test, the bar was lowered to the chest following which it was raised in a continuous movement until the elbows were fully extended. The maximum load for each participant was estimated between 0.8 and 1.2 times body mass or taken as advised by the participant. The increments used to build up to the estimated maximum were the same as those for the parallel squat (Figure 3.6). Following the estimated 1-RM attempt the load was increased or decreased by 2.5% to 5% depending upon whether the lift was successful or not. A lift was considered successful if the bar touched the chest during the descent and continued to move upward throughout the ascent without assistance. A lift was considered unsuccessful if the participant attempted to bounce the bar off the chest. During each lift spotters were placed at either end of the bar to aid the participant. A pilot study using physically active males revealed that 1-RMs were achieved within 4 lifts from the estimated 1-RM using this protocol (mean  $3.2 \pm 0.5$  lifts). As the bench-press was practiced during the 4-week familiarisation period all participants were considered competent in the movement.

### 3.46 Explosive strength

To provide further information as to the effects of the resistance training intervention, changes in measures of explosive strength were assessed. Vertical jumps were used to assess explosive strength as recommended by Harman, Garhammer and Pandorf (2000) and Young (1995). The participants performed static vertical jumps (SJ) under different load conditions: unloaded, with 30% of 1-RM parallel squat and with 60% of 1-RM parallel squat. These loads have been used in previous studies (Newton et al., 2002; Siegel et al., 2002). Three jumps under each load condition were performed with 3-minutes rest between each jump. Prior to the loaded conditions the participants performed a squat with the barbell to familiarise themselves with the load. The jumps were performed on a force platform (Kistler, type 9261A, Winterthur, Switzerland) measuring 0.6 m by 0.4 m. The signal was amplified by charge amplifiers (Kistler, type 5001, Winterthur, Switzerland) and data were sampled at 250 Hz, with the analogue signal converted to a digital signal using Pro-Vec software. The force recording was initiated prior to each jump and 3-seconds of data were recorded. The vertical force-time traces from the force platform were filtered using a fourth order Butterworth low-pass filter. A cut-off frequency of 17 Hz was selected for the unloaded jumps while the loaded jumps were filtered at 18 Hz.

The SJ required the participant to descend to a knee angle of  $90^{\circ}$  as indicated by an adjustable bar that touched the back of the participant's thighs when the correct angle was achieved (Figure 3.7). The correct knee angle was ensured by use of a goniometer. The exact position of the adjustable bar adjacent to the force platform was maintained to ensure that the depth of each participant's descent was consistent across the testing sessions. The  $90^{\circ}$  knee angle squat position was held for approximately 3-seconds, as indicated by the tester, following which the participant jumped for maximum height without a prior countermovement. Marks were placed on the force platform to ensure that the participants stood in the same place during each testing session.



**Figure 3.7** Experimental set-up for the loaded vertical jump protocols. Note: 1 = loaded barbell; 2 = adjustable bar set to each participant's  $90^{\circ}$  knee angle; 3 = force platform.

A standard 20 kg Olympic barbell and disks (Eleiko, Sweden) were used in the loaded jump conditions. In the unloaded jumps the participant's hands were placed on their neck to avoid

assistance during the movement. Spotters were employed during the loaded jump conditions and all of the jumps were performed under the guidance of the same tester in both testing sessions. A standardised warm-up consisting of jogging and dynamic exercises was performed prior to the jumps (Appendix A1.3). No static stretches were performed before the jumps to limit the impact that these exercises may have on performance during explosives movements (Kokkonen, Nelson & Cornwell, 1998).

### 3.461 Calculation of variables

To assess participant's abilities to move greater loads with a greater velocity, the variable of peak power (PP) was calculated for each load condition. PP was calculated from the vertical force-time trace during each jump. A jump was deemed to have started when the vertical force exceeded 10 N greater than mass of the participant or the mass of the participant and the loaded barbell during the held squat position. The mass of the participant or mass of the participant and the loaded barbell was recorded as the mean vertical GRF over a 0.20 second period (44 samples) during the held crouch position prior to the initiation of the jump. The force platform was calibrated prior to each testing session using weights of known magnitude.

The force-time trace was integrated using the trapezoid rule to produce an instantaneous velocity trace that was used in the calculation of PP. Specifically, the instantaneous vertical force was multiplied by the instantaneous velocity throughout the propulsive phase of the jump, yielding instantaneous power. The maximum value was recorded as PP as previously used with vertical jumps (Harman et al., 1990). The mean of 3 trials for each load condition was used in the analysis.

Using this protocol it was found that PP for the 3 load conditions did not change significantly across 4 testing sessions, indicating that familiarisation sessions were not required to obtain a reliable measure of PP (Moir et al., 2005). However, all the participants in the study performed a practice session during the 4-week familiarisation period to determine the appropriate height of the adjustable bar to ensure the correct descent position. The CV and ICC calculated for PP under each load condition are shown in Table 3.9 (Moir et al., 2005). Inspection of the data shows that the measure produced high test-retest reliability and low within-individual variation.

**Table 3.9** Coefficients of variation, intraclass correlation coefficients and associated 95% confidence limits for peak power output during the static vertical jumps.

Load condition	CV (%)	95% confidence limits		ICC	95% confidence limits	
		Lower	Upper		Lower	Upper
Unloaded	3.3	2.4	4.5	0.97	0.92	0.99
30% 1-RM	3.0	2.2	4.1	0.98	0.93	0.99
60% 1-RM	4.2	3.0	5.8	0.94	0.84	0.99

Note: CV = coefficient of variation; ICC = intraclass correlation coefficient; CL = confidence limits; 1-RM = one repetition maximum.

### 3.47 Anthropometric measures

Measures of body mass, height and selected skin-fold thicknesses were recorded for each participant. Body mass was measured using digital scales (EKS, model 9077, UK), while height was measured using a stadiometer (SECA, Germany). Skin-fold thicknesses were obtained with callipers (Harpenden, model AHSB, UK. 10 g.mm<sup>-1</sup> constant pressure) at the chest, mid-axillary, abdomen, suprailiac, subscapula, triceps, and thigh. At least 3 measures were obtained at each site, with the median of the measures used in the subsequent calculation. The seven-site equation developed by Jackson and Pollock (1985) was used to calculate percent body fat. Heyward (1998) reported that calculating the percentage of body fat using this method was appropriate for samples of young males.

### 3.5 Statistical analyses

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 11.0, SPSS Inc., Chicago, IL). Measures of central tendency and spread of the data were represented as means and standard deviations (SD). The analyses will be discussed in terms of the research questions.

#### *Research question 1.*

Does a period of resistance training in the absence of concurrent sprint training decrease accelerative sprint time immediately after the training period?

The outcome scores for the two groups on the assessment measures (sprint time, stride data, maximum and explosive strength, body mass and percent body fat) recorded pre and post-training were compared using a two-way analysis of variance (ANOVA: 2 groups x 2 testing occasions) with repeated measures on one factor (testing occasion). The alpha level was set at  $P < 0.05$ , allowing for Bonferroni adjustments for multiple comparisons. The magnitude of the changes for the experimental and control groups were assessed by calculating effect

sizes (ES) using the method outlined by Thomas et al. (1991). The ES were interpreted relative to each other.

### *Research question 2.*

Does a period of resistance training in the absence of concurrent sprint training cause a change in the co-ordination of movement during accelerative sprinting immediately after the training period?

The kinematic variables used in the assessment of co-ordination included joint angles at touch-down and toe-off, joint ranges of motion, phase-plane diagrams, discrete RP, CRP, CRP variability and spectral analyses. The pre and post-training joint angles at toe-off and touch-down and the joint ranges of motion were compared using an ANOVA model (2 groups x 2 testing occasions) with repeated measures on one factor (testing occasion). The alpha level set at  $P < 0.05$  with Bonferroni adjustments for multiple comparisons. The phase-plane diagrams for each joint were analysed using circular statistical methods. The pre and post-training mean direction of the data points in the mean phase-plane diagrams for each group were calculated as follows (Batschelet, 1981):

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n \cos \theta_i$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n \sin \omega_i$$

where  $\bar{x}$  = the mean  $x$  co-ordinate of the resultant vector,  $\bar{y}$  = the mean  $y$  co-ordinate of the resultant vector,  $n$  = the number of data points (101),  $\theta_i$  = the angular displacement at the  $i$ th point of the stride cycle,  $\omega_i$  = the angular velocity at the  $i$ th point of the stride cycle, and:

$$\phi_{\text{mean}} = \tan^{-1}(\bar{y}/\bar{x}) \text{ if } \bar{x} > 0, \text{ or}$$

$$\phi_{\text{mean}} = 180 + \tan^{-1}(\bar{y}/\bar{x}) \text{ if } \bar{x} < 0$$

where  $\phi_{\text{mean}}$  = the mean direction of the data points,  $\bar{x}$  = the mean  $x$  co-ordinate of the resultant vector,  $\bar{y}$  = the mean  $y$  co-ordinate of the resultant vector. The standard deviation of the data from the phase-plane diagrams was calculated from the length of the mean vector ( $\rho$ ) (Batschelet, 1981):



$$\rho = \sqrt{\bar{x}^2 + \bar{y}^2}$$

The standard deviation ( $\sigma$ ) is then:

$$\sigma = \sqrt{2(1 - \rho)}$$

The 95% confidence interval of the group means were calculated from the standard error of the mean ( $\hat{\sigma}_{\text{mean}}$ ), which was derived as follows (Fisher, 1993):

$$\hat{\sigma}_{\text{mean}} = 1/\sqrt{(n\rho\kappa)}$$

where  $n$  = the number of participants in the group (experimental group = 10; control group = 7),  $\rho$  = the length of the mean vector for the group,  $\kappa$  = the concentration parameter of the mean vector angle within each group (calculated from  $\rho$ ).

Pearson's product moment correlation coefficients were calculated between the pre and post-training phase angles of the phase-plane diagrams for each joint. The correlation coefficients were transformed using the Fisher Z-transformation and group differences were analysed using independent t-tests on the transformed correlation coefficients with alpha set at  $P < 0.05$ . Individual analyses of the phase-plane diagrams were also undertaken.

The pre and post-training measures of discrete RP, absolute mean CRP, and CRP variability (RMSE) during each stride were compared using an ANOVA model (2 groups x 2 testing occasions) with repeated measures on one factor (testing occasion). The alpha level was set at  $P < 0.05$  and Bonferroni adjustments were made for multiple comparisons. Changes in the mean ensemble CRP during each stride cycle were also assessed by constructing the 95% confidence intervals of the true mean for the pre and post-training mean ensemble graphs for the experimental and control groups, as discussed in Section 3.44. A significant difference was deemed to have occurred during a stride cycle at the point where the confidence intervals for the pre and post-training graphs did not overlap. Pearson's product moment correlation coefficients were calculated between the mean ensemble CRP graphs constructed for each participant during the pre and post-training testing session. The correlation coefficients were transformed using the Fisher Z-transformation and group differences in the transformed correlation coefficients were investigated by using independent t-tests with the alpha level set at  $P < 0.05$ . Individual changes in the RP measures were also assessed.

Changes in the spectral data for each joint were investigated using a two-way ANOVA. Specifically, the pre and post-training percentage changes in the power contained within the first 10 harmonics were entered into the ANOVA model (2 groups x 10 harmonics) with repeated measures on one factor (harmonic). The alpha level was set at  $P < 0.05$  with Bonferroni adjustments for multiple comparisons and differences between the harmonics were investigated using repeated contrasts.

### *Research question 3.*

Can the changes in sprint time and the co-ordination of movement as a result of resistance training be predicted from the magnitude of the gains in strength?

The association between the changes in strength (e.g. maximum strength) and the changes in sprint time and co-ordination measures were assessed using partial correlations, controlling for the effects of the other measure of strength (e.g. explosive strength).

The ability of the change in the measures of strength to predict the change in sprint time and co-ordination measures was assessed using linear regression models. For all models the changes in strength were the predictor variables, with the changes in sprint time or co-ordination measure as the outcome variables. It was ensured that there was a minimum of 5 participants for each predictor variable entered into the models, as recommended by Hair et al. (1998). The amount of variance in the outcome variable explained by the predictor variables within each model was expressed as the coefficient of determination ( $R^2$ ). The significance of the change in  $R^2$  from the addition of predictor variables was assessed using an ANOVA model, with alpha set at  $P < 0.05$ .

The contribution of each predictor variable to the outcome was assessed by calculating the standardised  $\beta$  coefficient. The significance of each  $\beta$  coefficient was assessed using a t-test with alpha set at  $P < 0.05$ . Multicollinearity within the models was assessed using the variance inflation factor (VIF) and tolerance ( $1/\text{VIF}$ ) (Field, 2000). The assumption of independent errors within each model was assessed using the Durbin-Watson statistic (Field, 2000).

## 4. RESULTS AND DISCUSSION

**Does a period of resistance training in the absence of concurrent sprint training decrease accelerative sprint time immediately after the training period?**

### 4.1 Results

#### 4.1.1 Sprint time

Table 4.1 shows the pre and post-training 10 m and 20 m mean sprint times for the experimental and control groups.

**Table 4.1** Pre and post-training 10 m and 20 m sprint times. Values are means  $\pm$  standard deviations.

Group	10 m time (s)		20 m time (s)	
	Pre-training	Post-training	Pre-training	Post-training
Experimental	1.84 $\pm$ 0.13	1.95 $\pm$ 0.13	3.21 $\pm$ 0.17	3.23 $\pm$ 0.21
Control	1.91 $\pm$ 0.11	1.96 $\pm$ 0.10	3.30 $\pm$ 0.21	3.36 $\pm$ 0.20

The results of the repeated measures ANOVA performed on the group sprint times are shown in Table 4.2. The significant main effect for testing occasion for the 10 m sprint was due to both groups increasing their time during the post-training testing session (mean difference between testing sessions: 0.08 s; 95% likely range: 0.04 – 0.11 s). However, the ES for the change by the experimental group (0.85) was greater than that for the control group (0.48). There were no other significant effects.

**Table 4.2** Results of the ANOVA performed on 10 m and 20 m sprint times. Main effects and interactions are shown.

Assessment	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
10 m time	23.18	<0.001	0.56	0.466	3.27	0.091
20 m time	3.45	0.079	1.50	0.239	0.79	0.388

Note: \* 1, 15 degrees of freedom.

#### 4.1.2 Maximum strength

The maximum normalised loads achieved for the measures of lower and upper-body maximum strength during the pre and post-training testing sessions for the experimental and control groups are shown in Table 4.3.

**Table 4.3** Pre and post-training measures of lower and upper-body maximum strength. Values are means  $\pm$  standard deviations.

Group	Parallel squat ( $\text{kg}\cdot\text{bm}^{-3/4}$ )		Bench-press ( $\text{kg}\cdot\text{bm}^{-3/4}$ )	
	Pre-training	Post-training	Pre-training	Post-training
Experimental	6.08 $\pm$ 0.77	7.26 $\pm$ 0.93	4.18 $\pm$ 0.66	4.89 $\pm$ 0.72
Control	5.61 $\pm$ 0.96	5.53 $\pm$ 0.88	3.91 $\pm$ 1.04	4.02 $\pm$ 1.13

Note:  $\text{kg}\cdot\text{bm}^{-3/4}$  = kilogram load per kilogram body mass to power  $3/4$ .

The results of the ANOVA are shown in Table 4.4. For both measures the increase across the testing sessions by the experimental group was significantly different from the change by the control group, producing significant group  $\times$  testing occasion interactions (ES parallel squat: experimental = 1.38; control = 0.09. ES bench-press: experimental = 1.03; control = 0.10).

**Table 4.4** Results of the ANOVA performed on the measures of lower and upper-body maximum strength. Main effects and interactions are shown.

Assessment	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Parallel squat	52.94	<0.001	6.64	0.021	69.55	<0.001
Bench-press	55.93	<0.001	1.38	0.258	28.56	<0.001

Note: \* 1, 15 degrees of freedom.

#### 4.13 Explosive strength

The pre and post-training group means for the measures of explosive strength are shown in Table 4.5.

**Table 4.5** Pre and post-training measures of explosive strength. Values are means  $\pm$  standard deviations.

Group	PP Unloaded (W)		PP 30% 1-RM (W)		PP 60% 1-RM (W)	
	Pre	Post	Pre	Post	Pre	Post
Experimental	4096	4260	3680	3899	3324	3642
	$\pm$ 789	$\pm$ 594	$\pm$ 716	$\pm$ 724	$\pm$ 788	$\pm$ 700
Control	3916	3883	3512	3453	3094	3073
	$\pm$ 557	$\pm$ 428	$\pm$ 623	$\pm$ 513	$\pm$ 423	$\pm$ 334

Note: PP = peak power output; 1-RM = one repetition maximum parallel squat; Pre = pre-training; Post = post-training.

The results of the ANOVA performed on the group means are shown in Table 4.6. Although the experimental group increased peak power output under the unloaded jump condition across the testing sessions the change was not significantly different from the change by the control group (ES: experimental = 0.23; control = 0.07). However, during both of the loaded vertical jump conditions the increase by the experimental group across the testing sessions was significantly different from the decrease by the control group, producing significant group x testing occasion interactions (ES PP 30% 1-RM: experimental = 0.30; control = 0.10. ES PP 60% 1-RM: experimental = 0.43; control = 0.06).

**Table 4.6** Results of the ANOVA performed on the measures of explosive strength. Main effects and interactions are shown.

Assessment	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Unloaded PP	1.37	0.260	0.84	0.373	3.15	0.096
30% 1-RM PP	6.65	0.021	0.89	0.361	20.00	<0.001
60% 1-RM PP	22.38	<0.001	1.70	0.212	29.10	<0.001

Note: \* 1, 15 degrees of freedom; PP = peak power output; 1-RM = one repetition maximum parallel squat.

#### 4.14 Kinematic and kinetic stride variables

The pre and post-training kinematic and kinetic variables during the first 3 strides of the 20 m sprint for the experimental and control groups are shown in Table 4.7. Statistical analysis of the variables during stride 1 revealed significant main effects for testing occasion for flight time and stride frequency (Table 4.8). These main effects were caused by both groups increasing flight time (mean difference between testing sessions: 6 ms; 95% likely range: 2 – 10 ms) and decreasing stride frequency (mean difference between testing sessions: -0.04 Hz; 95% likely range: -0.06 – -0.01 Hz) during the second testing session. There was a significant group x testing occasion interaction for stride length, with the experimental group increasing across the two testing sessions while the control group decreased. The analysis of the vertical impulse during the stance period of stride 1 revealed a significant main effect for testing occasion and a group x testing occasion interaction. Although both groups increased vertical impulse across the two testing sessions, the change by the experimental group was larger than that of the control group. However, the magnitude of the changes were similar for both groups (ES: experimental = 1.17; control = 0.97).

**Table 4.7** Pre and post-training kinematic and kinetic variables during the first 3 strides of the 20 m sprint. Values are means  $\pm$  standard deviations.

Stride	Group	Stride variable											
		Flight time (ms)		Stance time (ms)		Stride frequency (Hz)		Stride length (m)		Impulse x (N.s)		Impulse y (N.s)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Stride 1	Exp	321	329	148	154	2.15	2.09	2.05	2.09	123.4	114.0	104.8	151.0
		$\pm 28$	$\pm 28$	$\pm 17$	$\pm 24$	$\pm 0.18$	$\pm 0.19$	$\pm 0.18$	$\pm 0.20$	$\pm 28.2$	$\pm 31.2$	$\pm 36.8$	$\pm 41.7$
	Con	341	346	158	157	2.02	2.00	2.19	2.13	127.6	124.6	109.3	124.3
		$\pm 29$	$\pm 31$	$\pm 24$	$\pm 19$	$\pm 0.19$	$\pm 0.19$	$\pm 0.36$	$\pm 0.28$	$\pm 22.6$	$\pm 25.9$	$\pm 10.5$	$\pm 14.7$
Stride 2	Exp	320	328	133	135	2.22	2.18	2.59	2.64	96.0	75.4	110.9	163.3
		$\pm 31$	$\pm 28$	$\pm 14$	$\pm 19$	$\pm 0.20$	$\pm 0.19$	$\pm 0.22$	$\pm 0.23$	$\pm 15.0$	$\pm 20.7$	$\pm 35.0$	$\pm 49.1$
	Con	338	342	136	142	2.11	2.09	2.70	2.67	96.8	89.9	110.5	132.4
		$\pm 22$	$\pm 28$	$\pm 14$	$\pm 17$	$\pm 0.14$	$\pm 0.17$	$\pm 0.34$	$\pm 0.30$	$\pm 19.0$	$\pm 15.9$	$\pm 21.0$	$\pm 22.1$
Stride 3	Exp	324	334	122	125	2.26	2.20	3.02	3.09	84.8	70.8	122.1	169.4
		$\pm 31$	$\pm 31$	$\pm 15$	$\pm 18$	$\pm 0.21$	$\pm 0.21$	$\pm 0.28$	$\pm 0.27$	$\pm 14.8$	$\pm 17.5$	$\pm 44.5$	$\pm 52.7$
	Con	340	343	130	131	2.14	2.12	3.14	3.10	87.5	78.1	116.8	134.1
		$\pm 25$	$\pm 23$	$\pm 7$	$\pm 14$	$\pm 0.14$	$\pm 0.14$	$\pm 0.42$	$\pm 0.33$	$\pm 31.6$	$\pm 29.0$	$\pm 23.7$	$\pm 27.4$

Note: Impulse x = horizontal linear impulse during stance period; Impulse y = vertical linear impulse during stance period; Pre = pre-training; Post = post-training; Exp = experimental group; Con = control group.

**Table 4.8** Results of the ANOVA performed on the kinematic and kinetic variables during stride 1 of the 20 m sprint. Main effects and interactions are shown.

Stride variable	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Flight time	11.15	0.004	1.76	0.204	0.52	0.481
Stance time	1.08	0.315	0.45	0.512	1.42	0.251
Stride frequency	9.61	0.007	1.43	0.250	2.90	0.109
Stride length	0.14	0.718	0.57	0.464	4.82	0.044
Impulse x	2.52	0.133	0.32	0.581	0.68	0.423
Impulse y	108.06	<0.001	0.16	0.696	26.98	<0.001

Note: \* 1, 15 degrees of freedom; Impulse x = horizontal linear impulse during stance period; Impulse y = vertical linear impulse during stance period.

Table 4.9 shows the results of the ANOVA performed on the kinematic and kinetic variables recorded during stride 2. The significant main effect for testing occasion for the flight and stance times were caused by both groups increasing their flight time (mean difference between testing sessions: 6 ms; 95% likely range: 3 – 9 ms) and stance time (mean difference between testing session: 4 ms; 95% likely range: 1 – 8 ms) during the second testing session. As a result of the increases in flight and stance times, both groups decreased stride frequency across the testing sessions (mean difference between testing sessions: -0.03 Hz; 95% likely range: -0.05 – -0.02 Hz). There were significant group x testing occasion interactions for the horizontal and vertical impulse during stride 2, with the changes by the experimental group being larger than the changes by the control group (ES impulse x: experimental = 1.14; control = 0.39. ES impulse y: experimental = 1.23; control = 1.02).

The results of the statistical analysis performed on the kinematic and kinetic variables recorded during stride 3 are shown in Table 4.10. Both groups increased flight time during stride 3 across the testing sessions (mean difference between testing sessions: 6 ms; 95% likely range: 2 – 10 ms), producing a significant main effect for testing occasion. Similarly, there were significant main effects for testing occasion for stride frequency and horizontal impulse, with both groups decreasing their frequency (mean difference between testing sessions: -0.04 Hz; 95% likely range: -0.07 – -0.01 Hz) and horizontal impulse (mean difference between testing sessions: -11.71 N.s; 95% likely range: -17.24 – -6.18 N.s) during the second testing session. The analysis of the vertical impulse during the stance period of stride 3 revealed a significant main effect for testing occasion and a significant group x



testing occasion interaction. This was a result of both groups increasing the vertical impulse during the second testing session, and the increase by the experimental group being larger than the increase by the control group (ES: experimental = 0.97; control = 0.68).

**Table 4.9** Results of the ANOVA performed on the kinematic and kinetic variables during stride 2 of the 20 m sprint. Main effects and interactions are shown.

Stride variable	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Flight time	15.23	0.001	1.32	0.269	1.41	0.253
Stance time	4.58	0.049	0.41	0.530	1.15	0.301
Stride frequency	16.25	0.001	1.33	0.268	1.90	0.189
Stride length	0.13	0.721	0.30	0.591	1.69	0.213
Impulse x	18.96	0.001	0.88	0.364	4.71	0.047
Impulse y	60.91	<0.001	0.86	0.370	10.33	<0.001

Note: \* 1, 15 degrees of freedom; Impulse x = horizontal linear impulse during stance period; Impulse y = vertical linear impulse during stance period.

**Table 4.10** Results of the ANOVA performed on the kinematic and kinetic variables during stride 3 of the 20 m sprint. Main effects and interactions are shown.

Stride variable	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Flight time	9.67	0.007	0.85	0.371	2.79	0.115
Stance time	0.86	0.368	0.90	0.358	0.36	0.359
Stride frequency	6.34	0.024	1.32	0.268	2.34	0.147
Stride length	0.30	0.590	0.18	0.674	2.55	0.131
Impulse x	20.36	<0.001	0.21	0.656	0.77	0.394
Impulse y	48.60	<0.001	1.06	0.319	10.56	0.005

Note: \* 1, 15 degrees of freedom; Impulse x = horizontal linear impulse during stance period; Impulse y = vertical linear impulse during stance period.

There were significant positive correlations between the change in maximum strength (1-RM squat) and the change in vertical impulse during stride 1 ( $r = 0.700$ ,  $P = 0.004$ ), stride 2 ( $r = 0.717$ ,  $P = 0.003$ ) and stride 3 ( $r = 0.589$ ,  $P = 0.021$ ).

#### 4.15 Anthropometric measures

The pre and post-training group means for anthropometric measures of body mass and percent body fat are shown in Table 4.11. There were no significant main effects or group x testing occasion interactions for these measures following the training period ( $P > 0.05$ ).

**Table 4.11** Pre and post-training anthropometric measures. Values are means  $\pm$  standard deviations.

Group	Body mass (kg)		Body fat (%)	
	Pre-training	Post-training	Pre-training	Post-training
Experimental	79.6 $\pm$ 15.1	79.5 $\pm$ 13.7	9.7 $\pm$ 2.8	9.5 $\pm$ 2.1
Control	80.7 $\pm$ 9.5	79.9 $\pm$ 9.5	10.9 $\pm$ 4.2	11.6 $\pm$ 5.0

#### 4.2 Discussion

The principle aim of this investigation was to assess the effect of a resistance training intervention on accelerative sprint performance. It was found that an 8-week period of resistance training that increased measures of maximum and explosive strength did not decrease accelerative sprint time immediately after the training period. The increase in maximum squat strength was comparable to that reported in previous studies of similar duration investigating the effects of resistance training (Blazevich & Jenkins, 2002; Fry et al., 1991; Hennessy & Watson, 1994). McBride et al. (2002) investigated the effects of two resistance training interventions, one involving light jump squats (30% 1-RM) the other involving heavy jump squats (80% 1-RM). The heavy jump squat intervention produced greater improvements in peak power output during vertical jumps with heavy loads (80% 1-RM) than with lighter loads (30% 1-RM). This is similar to the findings of the present investigation. Moreover, McBride et al. (2002) reported an increase in 10 m sprint time as a result of the heavy jump squat resistance training, similar to that reported here.

Despite the increase in 10 m time for the experimental group reported in the present investigation, the overall 20 m time was not significantly different post-training. This indicates that the resistance training intervention was detrimental to performance over the initial 10 m, but may have improved the performance during the second 10 m of the 20 m sprint. A similar finding was reported by McBride et al. (2002) investigating the effect of a resistance training intervention involving heavy jump squats. It is likely that the two halves of the 20 m sprint (initial 10 m, second 10 m) represent distinct phases for the participants used in the present study, demanding different neuromuscular qualities (Delecluse, 1997;

Mero et al., 1992). Therefore, a resistance training intervention is likely to influence performance during the phases of sprinting in different ways (Delecluse et al., 1995a). Based on the present findings, and those of McBride et al. (2002), it appears that a resistance training intervention that increases explosive strength assessed under high load conditions is detrimental to performance during the initial acceleration phase of sprinting, but may improve performance as the athlete approaches maximum velocity.

An increase in 10 m time was also reported for the control group in the present investigation. It is likely that this finding was caused by the cessation of sprint activities for the duration of the training period by the members of the control group. Although the magnitude of the change by the control group was less than that for the experimental group, it is likely that a portion of the change by the experimental group was also as a consequence of refraining from sprint activity for the duration of the training period.

The kinematic and kinetic analyses of the first 3 strides of the 20 m sprint indicated that the increased time recorded for the initial 10 m by both the experimental and control groups was due mainly to a decrease in stride frequency. This finding provides tentative support for the proposal by Murphy et al. (2003) that stride frequency is more important than stride length in accelerative sprinting. The decrease in stride frequency recorded in the present study was caused by increases in the flight times resulting from an increase in the vertical impulse during the stance periods. The increase in vertical impulse was greater for the experimental group than the control group, and there were significant positive correlations between the changes in maximum strength and the change in vertical impulse.

Hunter et al. (2004a) identified the vertical velocity of the CoM at toe-off as a source of negative interaction between stride length and stride frequency, with the greater stride lengths and stride frequencies of elite sprinters resulting from a technique which allows high horizontal velocities and low vertical velocities of the CoM at toe-off. The forward rotation of the CoM over the stance leg prior to the proximal-to-distal extension of the joints constitutes an effective strategy that would allow the production of long strides at high stride frequencies during accelerative sprinting. This strategy involves controlling the direction of the GRF relative to the CoM during the stance periods and has been identified as a specific constraint associated with accelerative sprinting (Jacobs & Van Ingen Schenau, 1992). The rotation-extension strategy allows the angular acceleration of the lower limb joints to be effectively transformed to the translational acceleration of the CoM. The direction of the

GRF is controlled by the reciprocal action of the bi-articular hamstrings (HA) and rectus femoris (RF) muscles (Jacobs & Van Ingen Schenau, 1992). The strategy of rotating the body forward over the stance leg prior to a proximal-to-distal extension at each lower limb joint changes the orientation of the GRF with respect to the CoM during each stance period. During early stance, the GRF passes anterior to the CoM, decreasing the negative angular momentum of the body. As the body is rotated forward over the stance leg the GRF passes posterior to the CoM, increasing the negative angular momentum. It is at this time that the stance leg is extended and the CoM is translated horizontally. This rotation-extension strategy produces a high horizontal velocity of the CoM at toe-off while maintaining low vertical velocity, allowing for the optimal interaction between stride length and stride frequency.

However, the resistance training exercises used in the present investigation did not emphasise the rotation-extension strategy and so the specific co-ordination of the HA and RF muscle actions may not have been modified to suit the increased strength capabilities. This may have interfered with the appropriate control of the GRF direction relative to the CoM during stance. As such, the GRF may have been anterior to the CoM when joint extension occurred, preventing the effective horizontal translation of the CoM but increasing the vertical translation manifested in a decrease in horizontal impulse but an increase in the vertical impulse. Such a change would be expected to reduce stride frequency through an increase in flight time. Increasing the strength of the leg extensor muscles without concomitantly altering the co-ordination of the muscle actions may have elicited an earlier extension of the joints during stance, accelerating the CoM vertically. This could explain the strong positive correlations between the change in maximum strength and the change in vertical impulse during the first 3 strides of the sprint. Therefore, the changes in impulse reported here represent an adaptation to resistance training that could interfere with accelerative sprint performance.

While the increase in vertical impulse may interfere with accelerative sprinting, it has been proposed that greater maximum sprinting speeds are achieved by applying greater vertical forces to the ground during each stance period (Weyand et al., 2000). These authors proposed that greater average mass-specific vertical forces applied during the shorter stance durations associated with maximum velocity sprinting allowed faster sprinters to achieve the effective impulses, and therefore the flight times, necessary to reposition their swinging legs in preparation for the subsequent stance period. Therefore, the increased vertical impulse

reported in the present investigation may confer an adaptation to resistance training that is detrimental to accelerative sprinting but beneficial as the athlete approaches maximum velocity. This emphasises the mechanical differences between the distinct sprint phases and could explain why the time for the second 10 m of the 20 m sprint decreased slightly following the resistance training intervention, whereas the initial 10 m time increased. The specificity of resistance training exercises for the different sprint phases is also highlighted by this finding.

The effect of the specificity of resistance training exercises in relation to sprint running has been identified by Wilson et al. (1996). These authors showed that a programme of resistance training using exercises similar to those of the present investigation improved the performance in a sprint test performed on a cycle ergometer but did not improve 40 m sprint running time. It was proposed that since the application of force during the cycle test was in a vertical plane, the resistance training exercises developed strength in a movement that was more specific to cycling than to sprinting. Considering the findings of the present investigation, this explanation can be elaborated by suggesting that the resistance training exercises did not train the appropriate activation of the HA and RF muscles to adequately control the direction of the GRF relative to the CoM during the stance periods of accelerative sprinting, preventing the production of long strides at high stride frequencies. However, the adaptations as a result of the resistance training exercises were appropriate for the performance during maximum velocity sprinting where the application of greater vertical forces produces flight times that allow the repositioning of the swinging leg.

This investigation has shown that despite increases in measures of maximum and explosive strength, a period of resistance training does not improve accelerative sprint performance immediately after the training period. The increase in the sprint times over the initial 10 m of the 20 m sprint was caused by a decrease in stride frequency as a result of an increase in the flight time. The increase in flight time was caused by an increase in vertical impulse. Following the resistance training intervention the specific co-ordination pattern involved in the rotation-extension strategy that allows the production of long strides and high stride frequencies during acceleration was unlikely to have been adapted to the increased capacity (muscular strength) of the motor system. However, a detailed kinematic analysis of the sprinting movement during the first 3 strides of the 20 m sprint was undertaken to investigate the suggestion that the co-ordination pattern was disrupted following the resistance training intervention.

## 5. RESULTS AND DISCUSSION

**Does a period of resistance training in the absence of concurrent sprint training cause a change in the co-ordination of movement during accelerative sprinting immediately after the training period?**

### 5.1 Results

#### 5.1.1 Joint ranges of motion

The pre and post-training ranges of motion (RoM) about the joints during the first 3 strides of the 20 m sprint for the experimental and control groups are shown in Table 5.1.

**Table 5.1** Pre and post-training joint ranges of motion during the first 3 strides of the 20 m sprint. Values are means  $\pm$  standard deviations.

Stride	Group	Shoulder (degrees)		Hip (degrees)		Knee (degrees)		Ankle (degrees)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
Stride 1	Exp	128.32	134.98	62.70	63.67	90.49	95.50	43.47	43.92
		$\pm 12.17$	$\pm 6.89$	$\pm 7.68$	$\pm 10.03$	$\pm 12.97$	$\pm 11.94$	$\pm 5.38$	$\pm 7.25$
	Con	127.23	126.14	58.50	57.62	91.46	91.88	44.26	45.64
		$\pm 8.90$	$\pm 9.53$	$\pm 4.56$	$\pm 4.17$	$\pm 9.61$	$\pm 10.29$	$\pm 7.89$	$\pm 5.36$
Stride 2	Exp	126.97	134.06	59.65	62.06	90.24	97.78	44.03	43.76
		$\pm 13.83$	$\pm 9.58$	$\pm 8.17$	$\pm 10.64$	$\pm 11.13$	$\pm 14.05$	$\pm 5.66$	$\pm 5.19$
	Con	122.21	120.10	56.71	55.32	87.10	87.78	44.17	42.71
		$\pm 7.89$	$\pm 6.41$	$\pm 7.09$	$\pm 4.69$	$\pm 13.66$	$\pm 13.23$	$\pm 5.80$	$\pm 5.23$
Stride 3	Exp	125.25	132.17	59.90	61.38	98.53	104.13	40.92	40.23
		$\pm 13.29$	$\pm 9.32$	$\pm 6.50$	$\pm 8.99$	$\pm 11.04$	$\pm 12.29$	$\pm 6.22$	$\pm 6.37$
	Con	122.44	121.87	55.79	53.75	90.23	88.82	43.37	41.59
		$\pm 5.76$	$\pm 9.52$	$\pm 7.21$	$\pm 5.92$	$\pm 12.76$	$\pm 16.08$	$\pm 4.85$	$\pm 5.47$

Note: Pre = pre-training; Post = post-training; Exp = experimental group; Con = control group.

Statistical analysis of the data revealed significant group  $\times$  testing occasion interactions for the RoM about the shoulder joint during each stride due to the change by the experimental group across the two testing sessions being larger than that of the control group (Table 5.2). There were also significant group  $\times$  testing occasion interactions for the knee joint during the first 3 strides of the 20 m sprint, with the change in the RoM by the experimental group across the two testing sessions being larger from that of the control group (Table 5.2).



**Table 5.2** Results of the ANOVA performed on the range of motion about the shoulder and knee joints during the first 3 strides of the 20 m sprint. Main effects and interactions are shown.

Stride	Joint	Main effects				Interaction	
		Testing occasion		Group		F ratio*	P value
		F ratio*	P value	F ratio*	P value		
Stride 1	Shoulder	3.34	0.088	1.22	0.287	6.46	0.023
	Knee	9.62	0.007	0.06	0.816	6.90	0.019
Stride 2	Shoulder	2.63	0.126	3.77	0.071	8.94	0.009
	Knee	7.22	0.017	1.12	0.307	5.02	0.041
Stride 3	Shoulder	3.55	0.079	1.92	0.186	4.96	0.042
	Knee	1.86	0.193	3.67	0.075	5.20	0.038

Note: \* 1, 15 degrees of freedom.

### 5.12 Joint angles at touch-down and toe-off

The pre and post-training joint angles at touch-down during the first 3 strides of the 20 m sprint for the experimental and control groups are shown in Table 5.3. There were significant main effects for testing occasion for the shoulder angle during strides 1, 2 and 3, and for the hip angle during stride 3 (Table 5.4), with both groups increasing extension about the two joints at touch-down across the two testing sessions.

**Table 5.3** Pre and post-training joint angles at touch-down during the first 3 strides of the 20 m sprint. Values are means  $\pm$  standard deviations.

Stride	Group	Shoulder (degrees)		Hip (degrees)		Knee (degrees)		Ankle (degrees)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
Stride 1	Exp	-15.01	-25.32	115.54	116.98	124.28	123.81	110.09	112.28
		$\pm 25.77$	$\pm 20.73$	$\pm 10.44$	$\pm 10.43$	$\pm 5.21$	$\pm 6.76$	$\pm 8.79$	$\pm 4.93$
	Con	-9.68	-16.40	118.64	120.55	126.91	126.98	108.43	108.19
		$\pm 13.74$	$\pm 20.55$	$\pm 9.00$	$\pm 7.43$	$\pm 5.56$	$\pm 5.35$	$\pm 8.39$	$\pm 7.21$
Stride 2	Exp	-13.94	-21.54	120.15	122.48	131.67	131.67	110.91	113.95
		$\pm 23.18$	$\pm 17.11$	$\pm 8.78$	$\pm 7.83$	$\pm 5.01$	$\pm 5.79$	$\pm 7.33$	$\pm 6.56$
	Con	-4.78	-16.40	122.62	124.32	132.65	133.20	110.44	111.22
		$\pm 11.07$	$\pm 11.09$	$\pm 4.58$	$\pm 5.78$	$\pm 3.94$	$\pm 2.64$	$\pm 7.99$	$\pm 7.87$
Stride 3	Exp	-18.77	-26.21	126.90	130.15	136.90	138.23	114.07	116.75
		$\pm 18.09$	$\pm 15.73$	$\pm 7.68$	$\pm 6.43$	$\pm 6.54$	$\pm 4.75$	$\pm 6.95$	$\pm 6.78$
	Con	-12.54	-21.87	128.01	131.92	138.98	138.62	112.76	113.19
		$\pm 8.37$	$\pm 8.53$	$\pm 6.32$	$\pm 3.98$	$\pm 5.31$	$\pm 3.08$	$\pm 7.00$	$\pm 8.88$

Note: Pre = pre-training; Post = post-training; Exp = experimental group; Con = control group.



**Table 5.4** Results of the ANOVA performed on the shoulder and hip angles at touch-down during the first 3 strides of the 20 m sprint. Main effects and interactions are shown.

Stride	Joint	Main effects				Interaction	
		Testing occasion		Group		F ratio*	P value
		F ratio*	P value	F ratio*	P value		
Stride 1	Shoulder†	8.04	0.013	0.51	0.488	0.36	0.558
	Hip	1.48	0.242	0.54	0.474	0.03	0.864
Stride 2	Shoulder	10.02	0.006	1.64	0.220	1.74	0.208
	Hip	2.33	0.148	0.42	0.525	0.06	0.813
Stride 3	Shoulder‡	9.58	0.007	1.29	0.274	0.42	0.529
	Hip	5.88	0.028	0.19	0.667	0.50	0.491

Note: \* 1, 15 degrees of freedom. † Levene's test for equality of error variances for pre-training values ( $F(1,15) = 6.67$ ,  $P = 0.021$ ). ‡ Levene's test for pre-training values ( $F(1,15) = 6.21$ ,  $P = 0.025$ ).

The pre and post-training joint angles at toe-off during the first 3 strides of the 20 m sprint for the experimental and control groups are shown in Table 5.5.

**Table 5.5** Pre and post-training joint angles at toe-off during the first 3 strides of the 20 m sprint. Values are means  $\pm$  standard deviations.

Stride	Group	Shoulder (degrees)		Hip (degrees)		Knee (degrees)		Ankle (degrees)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
Stride 1 start	Exp	41.36	39.69	147.48	149.69	154.26	155.35	133.20	135.47
		$\pm 21.22$	$\pm 15.27$	$\pm 8.38$	$\pm 6.33$	$\pm 6.60$	$\pm 6.57$	$\pm 7.55$	$\pm 3.72$
	Con	49.69	41.61	152.37	152.91	156.72	156.68	133.94	131.57
		$\pm 22.16$	$\pm 26.99$	$\pm 6.94$	$\pm 8.80$	$\pm 7.64$	$\pm 7.37$	$\pm 9.73$	$\pm 7.10$
Stride 1 end	Exp	54.29	53.57	154.61	158.01	152.75	154.64	130.14	133.87
		$\pm 12.07$	$\pm 7.34$	$\pm 6.26$	$\pm 5.48$	$\pm 5.55$	$\pm 5.56$	$\pm 5.93$	$\pm 3.07$
	Con	55.47	49.08	158.95	157.69	154.57	153.51	130.25	128.07
		$\pm 8.90$	$\pm 14.29$	$\pm 8.00$	$\pm 7.33$	$\pm 6.09$	$\pm 6.69$	$\pm 8.03$	$\pm 6.44$
Stride 2 end	Exp	54.46	55.43	158.48	162.74	150.34	155.95	127.25	130.33
		$\pm 10.20$	$\pm 6.79$	$\pm 6.62$	$\pm 5.60$	$\pm 6.50$	$\pm 7.00$	$\pm 5.58$	$\pm 6.88$
	Con	58.95	51.01	160.60	160.05	152.24	151.20	125.16	126.82
		$\pm 4.69$	$\pm 10.07$	$\pm 8.01$	$\pm 5.93$	$\pm 4.94$	$\pm 6.24$	$\pm 6.34$	$\pm 5.04$
Stride 3 end	Exp	51.85	52.24	161.98	165.58	148.95	152.78	130.55	133.70
		$\pm 9.15$	$\pm 6.60$	$\pm 5.84$	$\pm 5.61$	$\pm 6.05$	$\pm 5.42$	$\pm 4.65$	$\pm 3.89$
	Con	54.59	51.06	166.21	164.98	150.32	151.16	128.34	128.99
		$\pm 6.99$	$\pm 10.23$	$\pm 8.24$	$\pm 6.11$	$\pm 6.82$	$\pm 6.94$	$\pm 9.38$	$\pm 5.24$

Note: Pre = pre-training; Post = post-training; Exp = experimental group; Con = control group.

There were significant group x testing occasion interactions for the toe-off angles at the hip and knee joints during the first 3 strides, with the changes by the experimental group across the two testing sessions being larger than those of the control group (Table 5.6). A significant group x testing occasion interaction for the toe-off angle about the ankle joint at the end of stride 1 was caused by the change for the experimental group across the two testing sessions being greater than that of the control group (Table 5.6). There was a significant group x testing occasion interaction for the toe-off angle about the shoulder joint during stride 2, with the decrease in flexion by the control group being greater than the increase in flexion by the experimental group.

**Table 5.6** Results of the ANOVA performed on the joint angles at toe-off during the first 3 strides of the 20 m sprint. Main effects and interactions are shown.

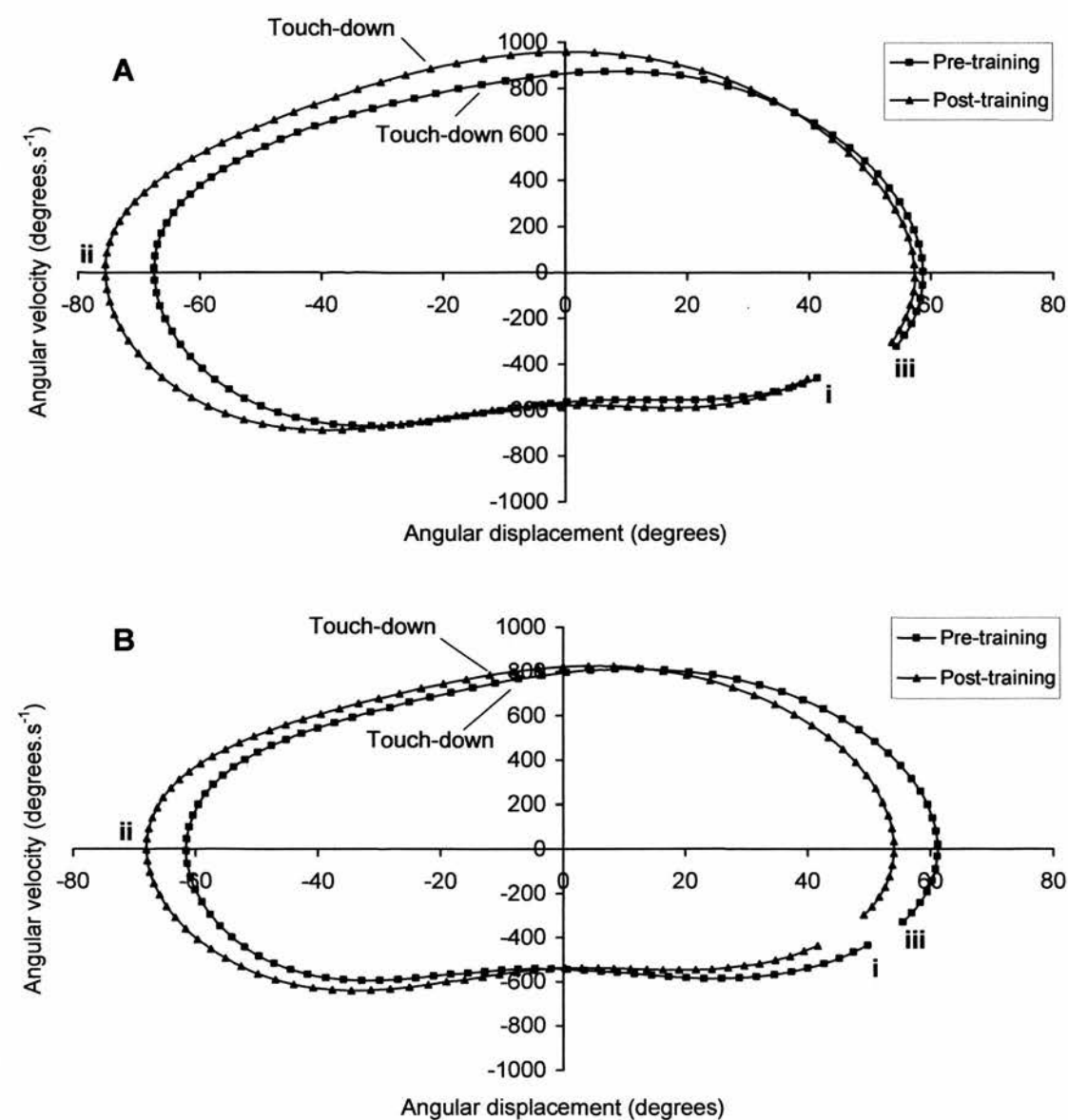
Stride	Joint	Main effects				Interaction	
		Testing occasion		Group		F ratio*	P value
		F ratio*	P value	F ratio*	P value		
Stride 1 start	Shoulder	2.72	0.120	0.26	0.616	1.18	0.295
	Hip	1.07	0.318	1.33	0.267	0.40	0.539
	Knee	0.47	0.505	0.32	0.579	0.54	0.473
	Ankle	0.00	0.975	0.25	0.624	2.41	0.141
Stride 1 end	Shoulder	2.60	0.128	0.12	0.74	1.64	0.219
	Hip	3.28	0.090	0.389	0.54	15.39	0.001
	Knee	0.61	0.447	0.014	0.91	7.83	0.013
	Ankle†	0.34	0.568	1.215	0.29	5.01	0.041
Stride 2 end	Shoulder	4.82	0.044	7.89	0.013	0.00	0.994
	Hip	2.79	0.115	0.009	0.93	4.72	0.046
	Knee	3.77	0.071	0.243	0.63	7.97	0.013
	Ankle	3.15	0.096	1.103	0.31	0.28	0.603
Stride 3 end	Shoulder	0.79	0.388	1.24	0.28	0.05	0.836
	Hip	1.60	0.225	0.365	0.56	6.73	0.020
	Knee	12.66	0.003	0.002	0.97	5.19	0.038
	Ankle	1.62	0.223	1.975	0.18	0.70	0.415

Note: \* 1, 15 degrees of freedom. † Levene's test for equality of error variances for the pre-training values ( $F(1,15) = 5.05$ ,  $P = 0.040$ ).

### 5.13 Phase-plane diagrams

Exemplar phase-plane diagrams for the shoulder, hip, knee and ankle joints during the first stride of the 20 m sprint are shown in Figures 5.1, 5.2, 5.3 and 5.4, respectively. These diagrams show the mean curves for the experimental and the control groups. Each diagram

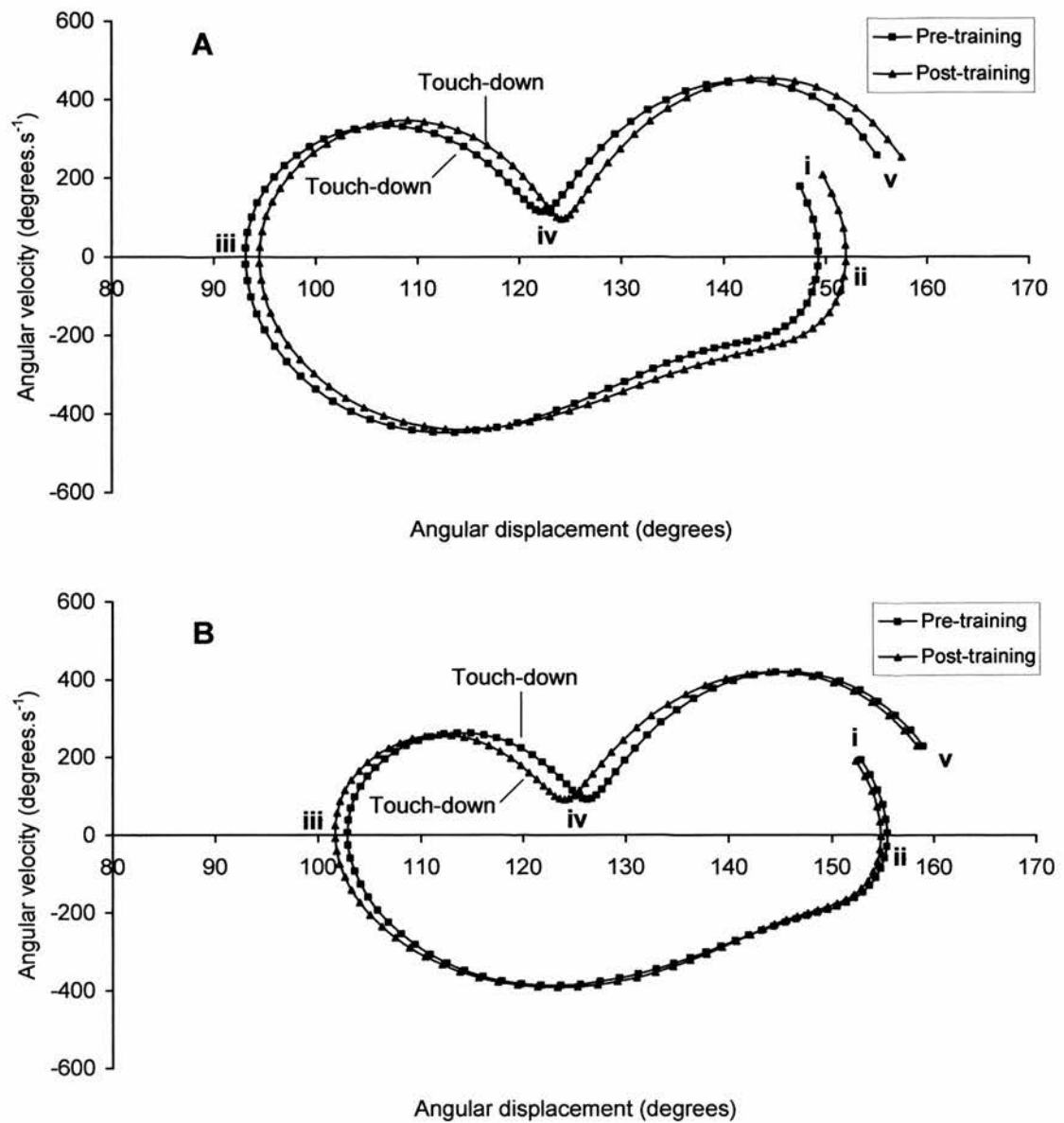
evolves in a clockwise direction from toe-off to ipsilateral toe-off. The changes shown in these diagrams are typical of those across the other strides.



**Figure 5.1** Pre and post-training phase-plane diagrams of the shoulder joint for the experimental group (A) and the control group (B) during stride 1 of the 20 m sprint. Values are means. Note: i = start of stride cycle; ii = transition from extension to flexion; iii = end of stride cycle (toe-off).

The mean pre and post-training graphs of the shoulder joint for the experimental and control groups during stride 1 (Figure 5.1) shows that the pre and post-training curves follow similar trajectories for both groups. The control group reduced the angular displacement (flexion) at

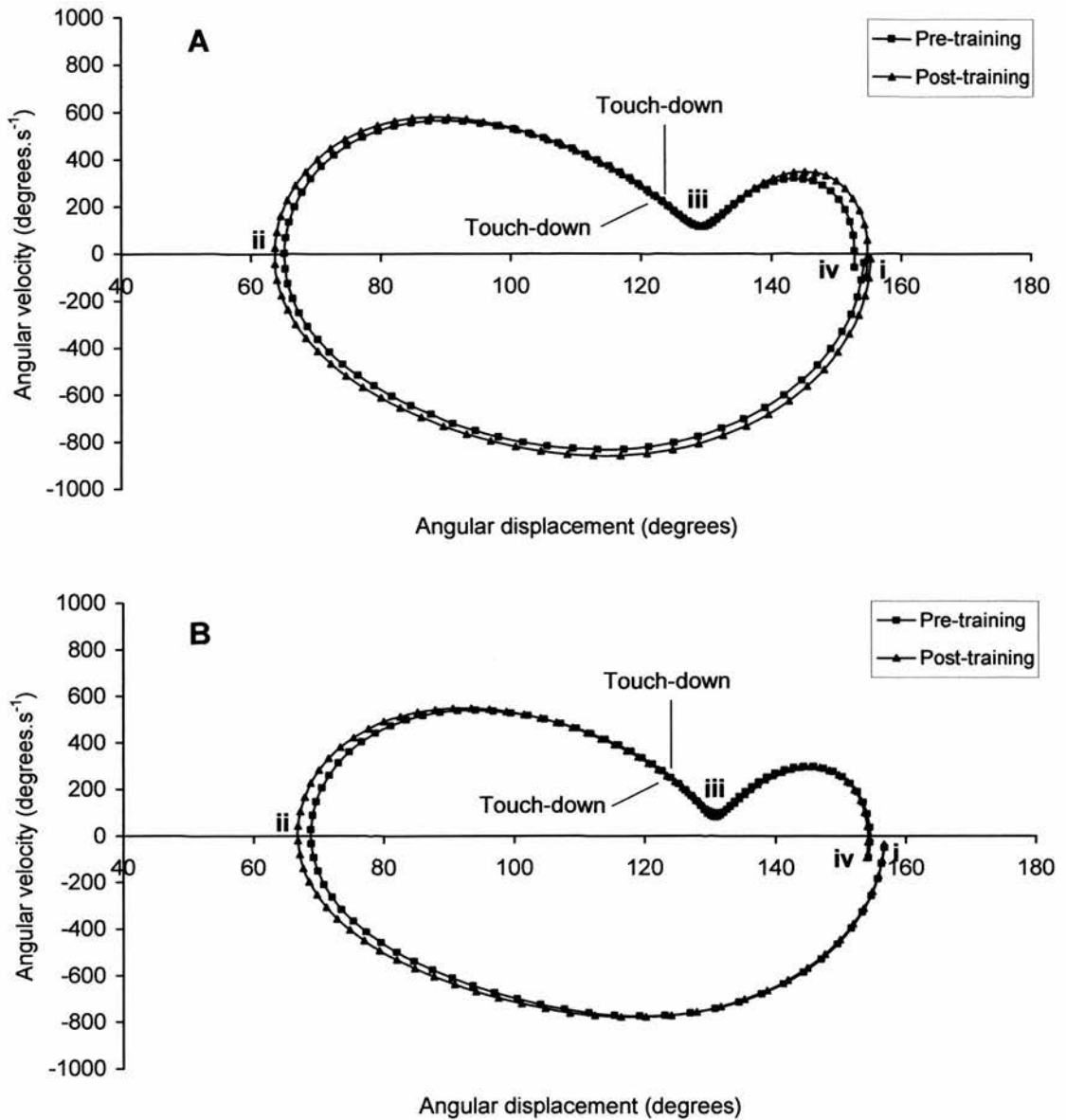
the beginning and end of the stride cycle across the two testing sessions, although this change was not significantly different from that of the experimental group ( $P > 0.05$ ). The transition from extension to flexion occurred at around 45% of the stride cycle for both groups, although the displacement at the point of maximum extension was greater post-training compared to the pre-training values for both groups. The increase by the experimental group contributed to the post-training increase in the RoM about the shoulder joint ( $P = 0.023$ ).



**Figure 5.2** Pre and post-training phase-plane diagrams of the hip joint for the experimental group (A) and the control group (B) during stride 1 of the 20 m sprint. Values are means. Note: i = start of stride cycle; ii = transition from extension to flexion; iii = transition from flexion to extension; iv = local minima in angular velocity; v = end of stride cycle (toe-off).

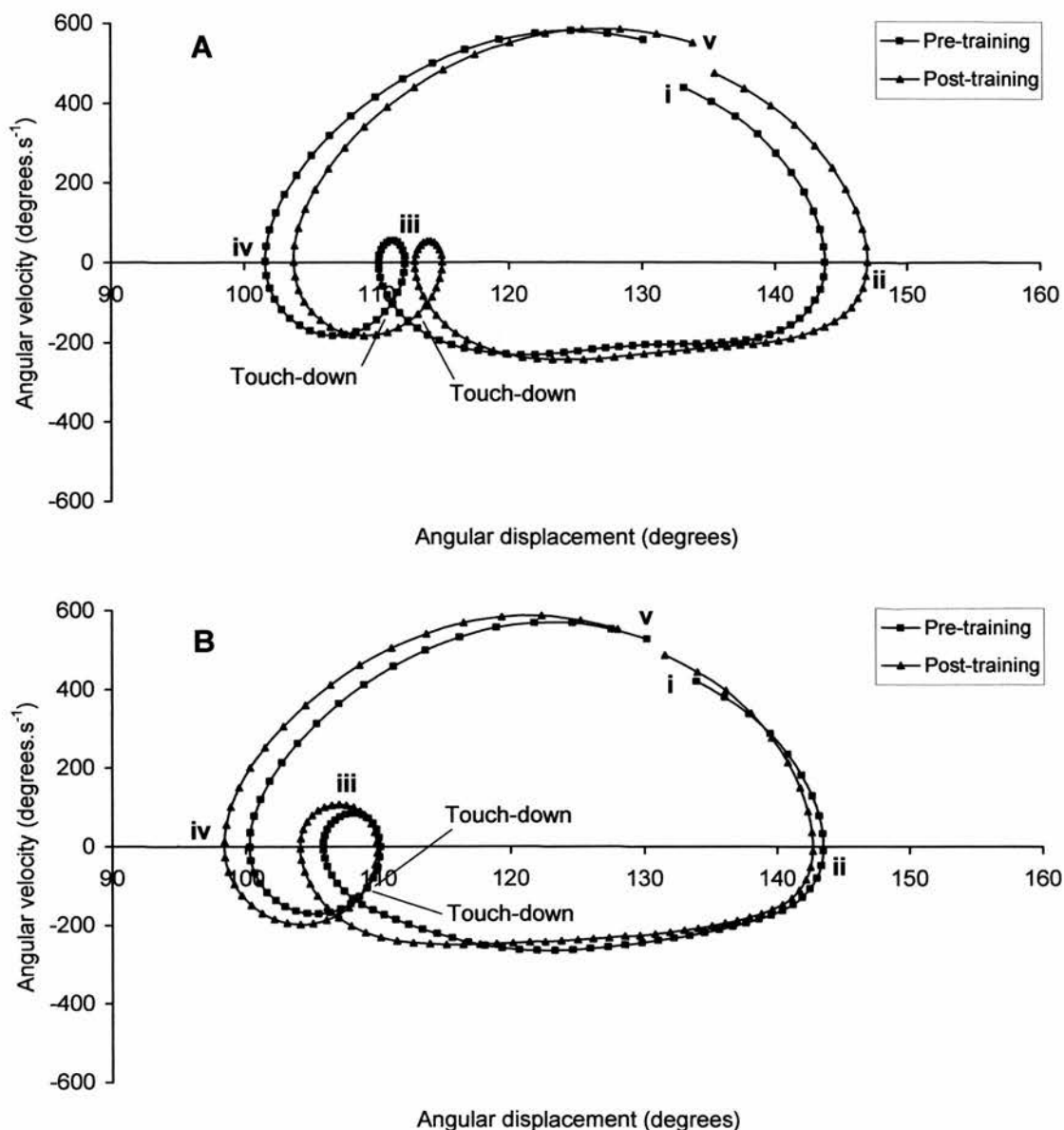
Figure 5.2 shows the mean pre and post-training phase-plane diagrams of the hip joint during stride 1 for both groups. Although the experimental group increased extension at the beginning of the stride cycle during the post-training testing sessions, the increase was not significantly different from the change by the control group ( $P > 0.05$ ). The transitions from extension to flexion just after toe-off occurred at similar points of the stride cycle for both groups across the two testing sessions (5% for the experimental group; 6% for the control group). Similarly, the transitions from flexion to extension occurred at the same percentage of the stride cycle across the testing sessions for both groups (49% for the experimental group; 50% for the control group). For both groups, hip extension slowed prior to touch-down (touch-down = 68% of stride cycle for experimental group pre and post-training; 68% pre-training and 69% post-training for the control group), and the local minima in angular velocity (extension) occurred at 77% of the stride cycle for both groups pre and post-training. At the end of the stride cycle (toe-off) the experimental group increased extension at the hip during the post-training testing session, a change that was greater than that of the control group ( $P = 0.001$ ).

Figure 5.3 shows the mean pre and post-training phase-plane diagrams of the knee joint for the experimental and control groups during stride 1. The pre and post-training curves for both groups followed very similar trajectories. There was very little change across the testing sessions in the angular displacement and velocity values at the beginning of the stride cycles for both groups. Similarly, the transition from flexion to extension occurred at around 36% of the stride cycle for both groups' pre and post-training graphs. These transitions occurred prior to the flexion-extension transition seen at the hip joint. During the post-training testing session both groups increased flexion slightly at the transition point. For both groups, knee extension slowed prior to touch-down. There were no significant differences in the change in angular displacement at touch-down between the groups ( $P > 0.05$ ). The local minima in angular velocity occurred at 75% of the stride cycle for both groups, which was slightly prior to the same events in the hip joint phase-plane diagrams. At the end of the stride the experimental group increased knee extension across the testing sessions, a change that was significantly different from the decrease of the control group ( $P = 0.013$ ). The increase in extension at toe-off and the increase in flexion at the flexion-extension transition for the experimental group combined to increase the RoM about the knee joint following the resistance training intervention, a change that was greater than that of the control group ( $P = 0.019$ ).



**Figure 5.3** Pre and post-training phase-plane diagrams of the knee joint for the experimental group (A) and the control group (B) during stride 1 of the 20 m sprint. Values are means. Note: i = start of stride cycle; ii = transition from flexion to extension; iii = local minima in angular velocity; iv = end of stride cycle (toe-off).

The mean pre and post-training phase-plane diagrams of the ankle joint for both groups during stride 1 are shown in Figure 5.4. At the beginning of the stride cycle the experimental group increased plantar flexion post-training while the control group reduced plantar flexion, although the changes were not significantly different ( $P > 0.05$ ). The transitions between plantar flexion and dorsi flexion occurred at similar percentages of the stride cycles for both groups during both testing sessions.



**Figure 5.4** Pre and post-training phase-plane diagrams of the ankle joint for the experimental group (A) and the control group (B) during stride 1 of the 20 m sprint. Values are means. Note: i = start of stride cycle; ii = transition from plantar to dorsi flexion; iii = plantar flexion; iv = transition from dorsi to plantar flexion; v = end of stride cycle (toe-off).

The 'loops' at the bottom of the graphs in Figure 5.4 (point iii) occurred at 58% of the stride cycle for the control group during both testing sessions and represent a time when the ankle joint momentarily plantar flexes prior to the beginning of stance. The same event occurred at 59% of the stride cycle during the pre-training testing session for the experimental group and 57% of the stride cycle post-training. Although the experimental group increased plantar flexion at touch-down during the post-training testing session, the change was not



significantly different from that of the control group ( $P > 0.05$ ). The transition from dorsiflexion to plantar flexion during stance occurred at the same point across the testing sessions for the experimental group (83%) and control group (84%). At these times, both the hip and knee joints had begun to increase the velocity of extension for toe-off. At the end of the stride cycle (toe-off) the experimental group increased plantar flexion across the testing sessions, although the change was not significantly different from the decrease by the control group ( $P > 0.05$ ).

Table 5.7 shows the group means and associated 95% confidence limits for the direction of the mean vector calculated from the phase-plane diagrams for the shoulder, hip, knee and ankle joints during each of the first 3 strides from the pre and post-training testing sessions. The confidence limits overlap indicating that there were no significant changes in the direction of the mean vector for either group across the testing sessions.

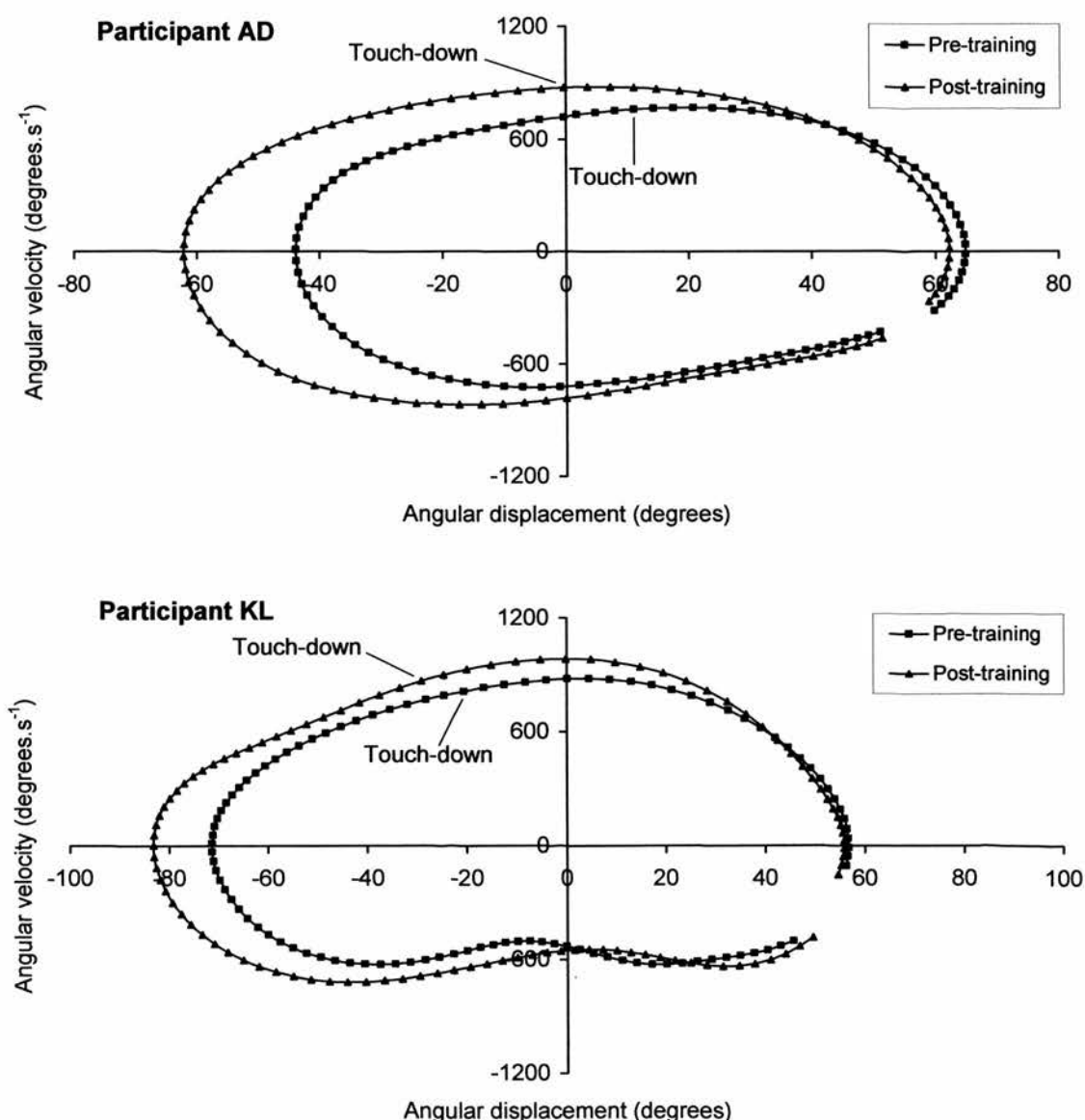
There were large correlation coefficients between the pre and post-training phase angles calculated from the joint phase-plane diagrams for the experimental and control groups during each stride ( $r \geq 0.90$ ). The large correlation coefficients for each joint during the first 3 strides indicated strong associations between the pre and post-training phase-angles for the experimental and control groups. Independent t-tests performed on the correlation coefficients following Fisher Z-transformation revealed that the two groups did not differ significantly ( $P > 0.05$ ).

Figures 5.5 through to 5.12 show the phase-plane diagrams for the shoulder, hip, knee and ankle joints during stride 1 for two sets of participants from the experimental group. Participants AD and KL responded to the resistance training intervention by increasing 10 m sprint time by 1% and 2%, respectively. Because of the small changes in sprint time these participants are referred to as 'maintenance responders'. Conversely, participants DG and IF increased 10 m sprint time by 14% and 9%, respectively, following the resistance training intervention and are referred to as 'increase responders'. The changes in the phase-plane diagrams shown are typical of those during strides 2 and 3 for these participants. The inclusion of these contrasting sub-sets of the experimental participants allows the identification of individual responses in the behaviour of the joints that may have occurred following the resistance training intervention and contributed to the changes in sprint time.

**Table 5.7** Group means and associated 95% confidence limits for the direction of the mean vector calculated from the phase-plane diagrams for the shoulder, hip, knee and ankle joints during the first 3 strides of the 20 m sprint.

Stride	Group	Joint							
		Shoulder (degrees)		Hip (degrees)		Knee (degrees)		Ankle (degrees)	
		Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training	Pre-training	Post-training
1	Exp	Mean	179.06	179.26	181.44	180.62	180.58	179.73	181.07
		95% CL	175 – 183	176 – 182	178 – 185	178 – 183	177 – 184	176 – 183	179 – 184
	Con	Mean	179.25	180.58	181.01	180.31	179.28	179.76	179.70
		95% CL	175 – 183	177 – 184	178 – 184	177 – 183	173 – 185	176 – 184	177 – 183
2	Exp	Mean	178.67	179.14	180.42	179.49	180.34	180.02	179.87
		95% CL	174 – 183	176 – 183	176 – 185	177 – 182	177 – 184	174 – 183	176 – 183
	Con	Mean	179.02	180.42	179.62	180.50	180.28	179.23	180.41
		95% CL	177 – 182	172 – 189	174 – 186	178 – 184	178 – 183	176 – 183	177 – 184
3	Exp	Mean	181.02	180.90	180.51	179.40	181.02	180.60	179.72
		95% CL	179 – 183	176 – 184	178 – 183	177 – 182	178 – 184	179 – 183	178 – 182
	Con	Mean	180.90	180.81	178.91	179.27	179.27	178.52	180.47
		95% CL	172 – 190	178 – 184	176 – 182	177 – 182	176 – 183	175 – 182	177 – 184

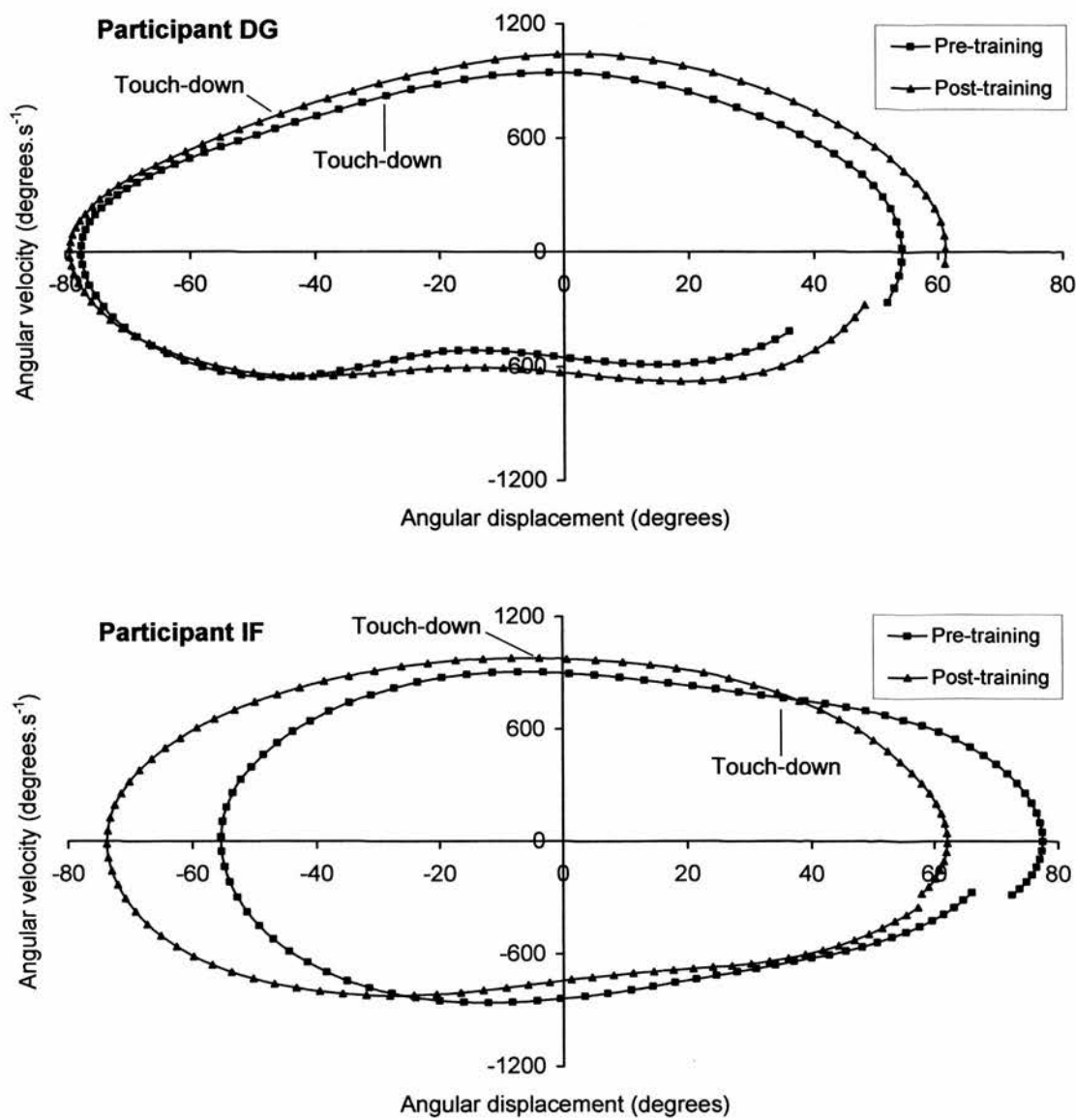
Note: Exp = experimental group; Con = control group; CL = confidence limits.



**Figure 5.5** Pre and post-training phase-plane diagrams of the shoulder joint during stride 1 for two 'maintenance responders' from the experimental group. Values are means. Note: Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.

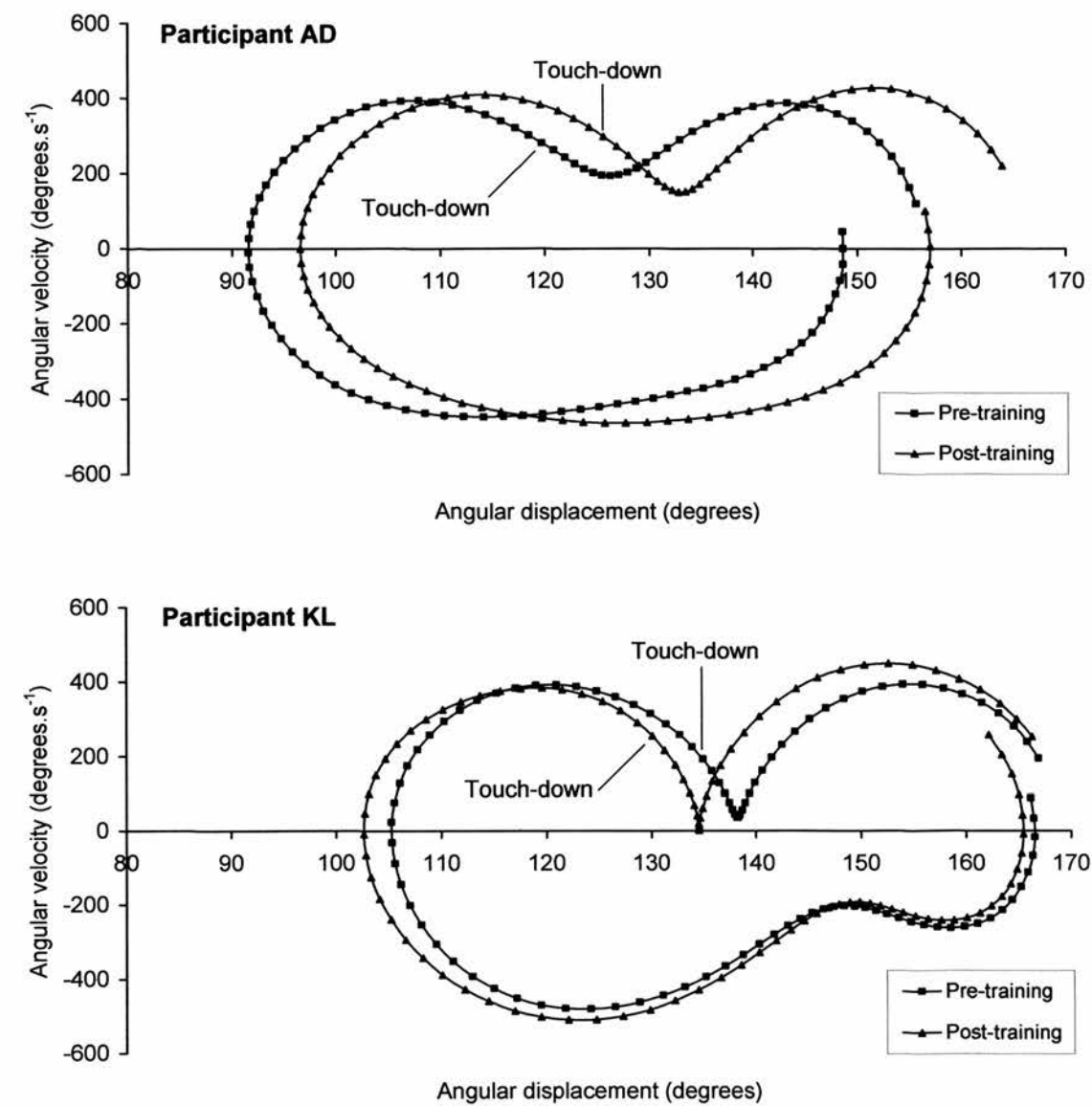
The 'maintenance responders' increased the RoM about the shoulder joint (AD = 15°; KL = 11°) more than the 'increase responders' (DG = 6°; IF = 3°) following the resistance training intervention (Figures 5.5 & 5.6). These increases in the RoM were mainly caused by an increase in the extension about the shoulder joint at the extension-flexion transition. The 'maintenance responders' maintained the overall temporal behaviour about the shoulder joint following the resistance training. For example, the transition from extension to flexion occurred at 44% of the pre and post-training stride cycles for participant AD and at 48% for

participant KL. However, this same event was delayed across the testing sessions for the two ‘increase responders’. At pre-training the extension-flexion transition occurred at 46% of the stride cycle for participant DG and 44% for participant IF. Post-training, these events occurred at 50% and 47% of the stride cycle for participants DG and IF, respectively. Although all participants increased the extension about the shoulder joint at touch-down post-training, participant IF demonstrated a 40° increase which was much greater than that for the other participants.



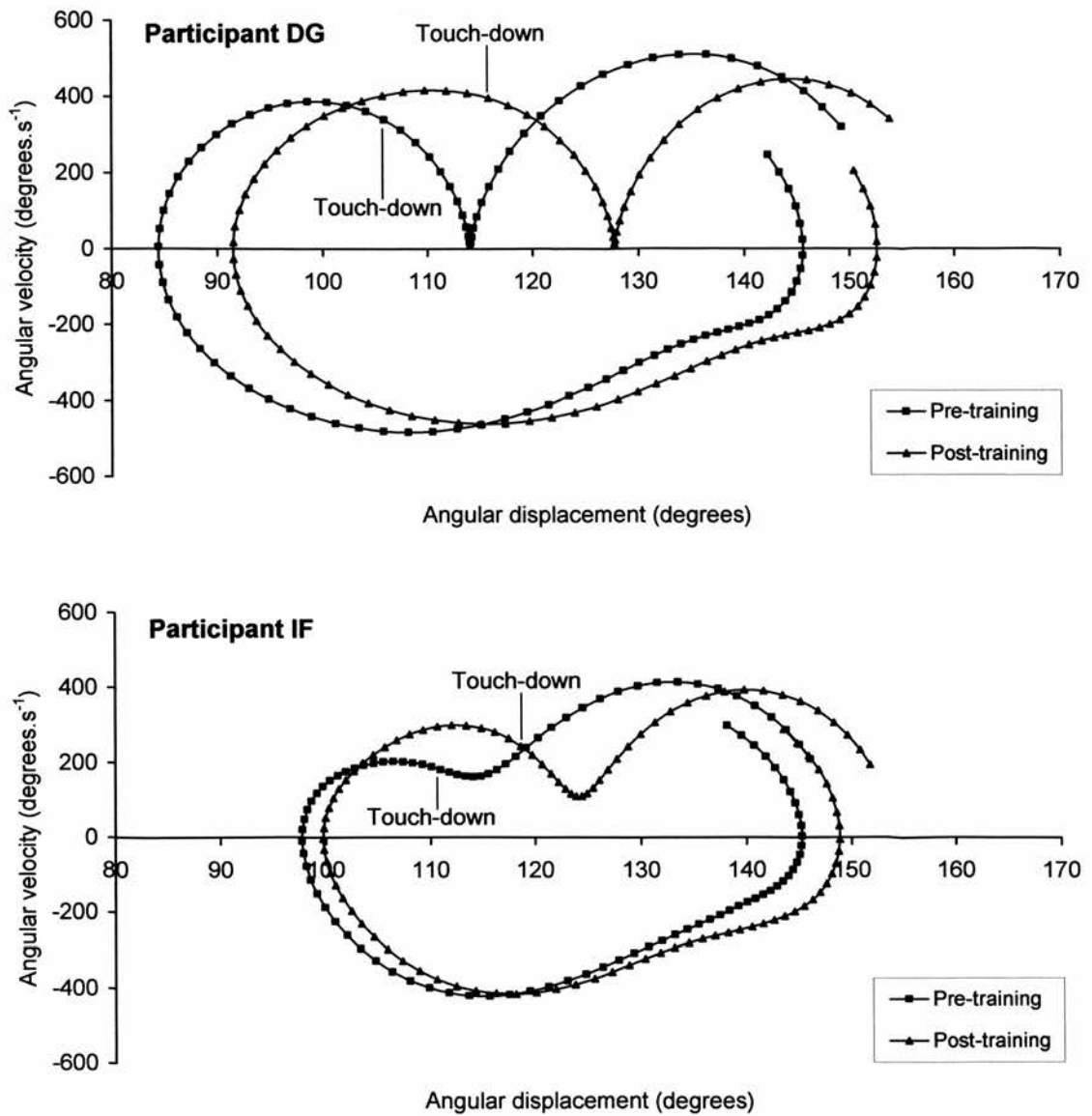
**Figure 5.6** Pre and post-training phase-plane diagrams of the shoulder joint during stride 1 for two ‘increase responders’ from the experimental group. Values are means. Note: Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

Figures 5.7 and 5.8 show the phase-plane diagrams of the hip during stride 1 for the ‘maintenance’ and ‘increase’ responders, respectively. All of the participants increased the RoM about the hip joint following the resistance training intervention.



**Figure 5.7** Pre and post-training phase-plane diagrams of the hip joint during stride 1 for two ‘maintenance responders’ from the experimental group. Values are means. Note: Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.

With the exception of KL, all of the participants increased the extension at the beginning of the stride across the testing sessions. Participant KL actually reduced the extension about the hip joint at the beginning of the stride, although the angular velocity (extension) was much greater post-training.



**Figure 5.8** Pre and post-training phase-plane diagrams of the hip joint during stride 1 for two 'increase responders' from the experimental group. Values are means. Note: Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

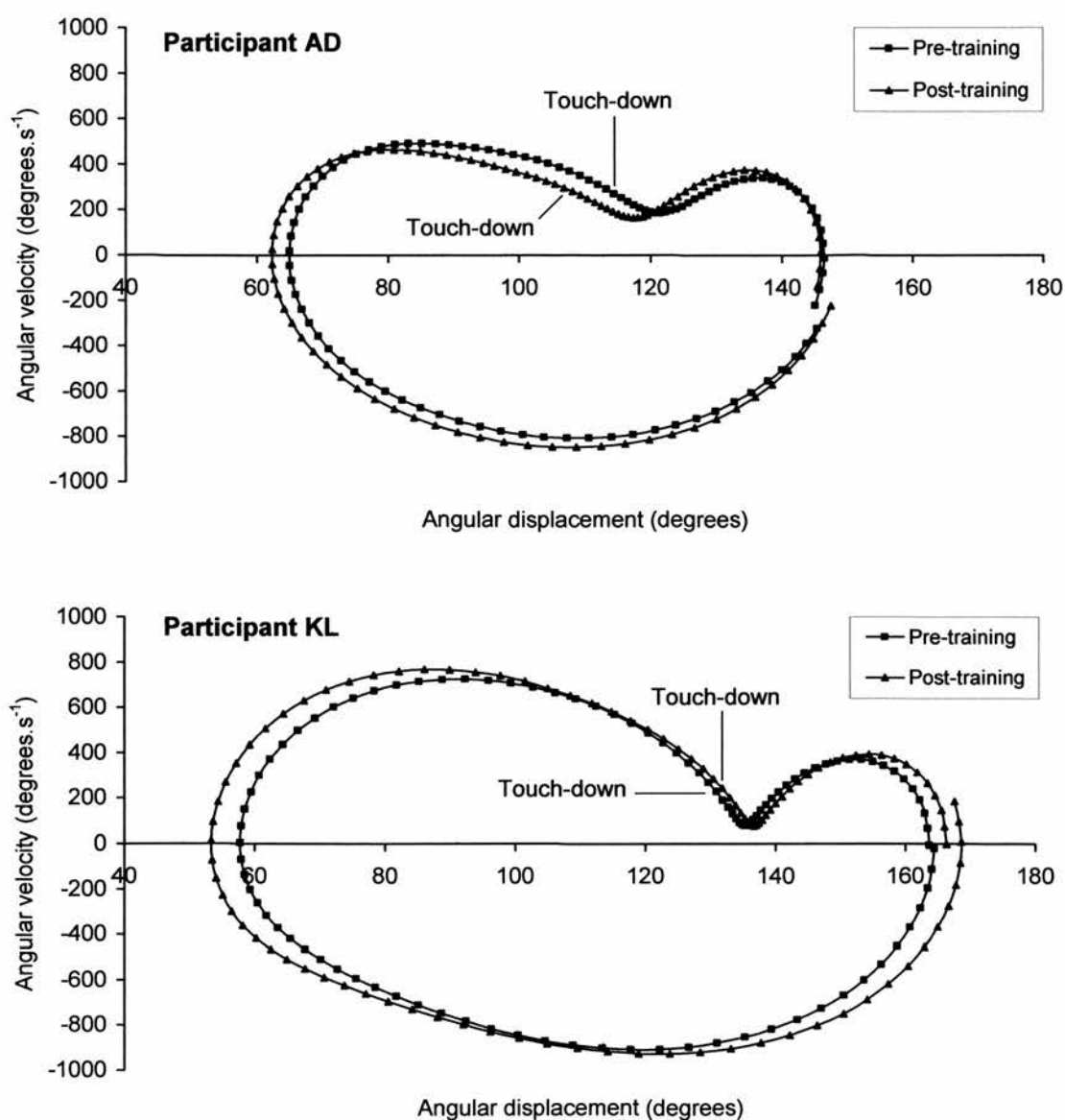
While the 'maintenance responders' maintained the temporal behaviour about the hip joint across the testing sessions, the 'increase responders' tended to alter certain aspects. For example, the extension-flexion and flexion-extension transitions occurred earlier during the post-training stride cycle for participant IF. Despite these temporal changes, the local minima in angular velocity following touch-down occurred at very similar times during the pre and post-training strides, although hip extension was increased post-training (Figure 5.8). Conversely, participant DG maintained the timing of the extension-flexion and flexion-

extension transitions during the flight period but delayed the local minimum in angular velocity post-training (pre-training: 77% of stride cycle; post-training: 81% of stride cycle).

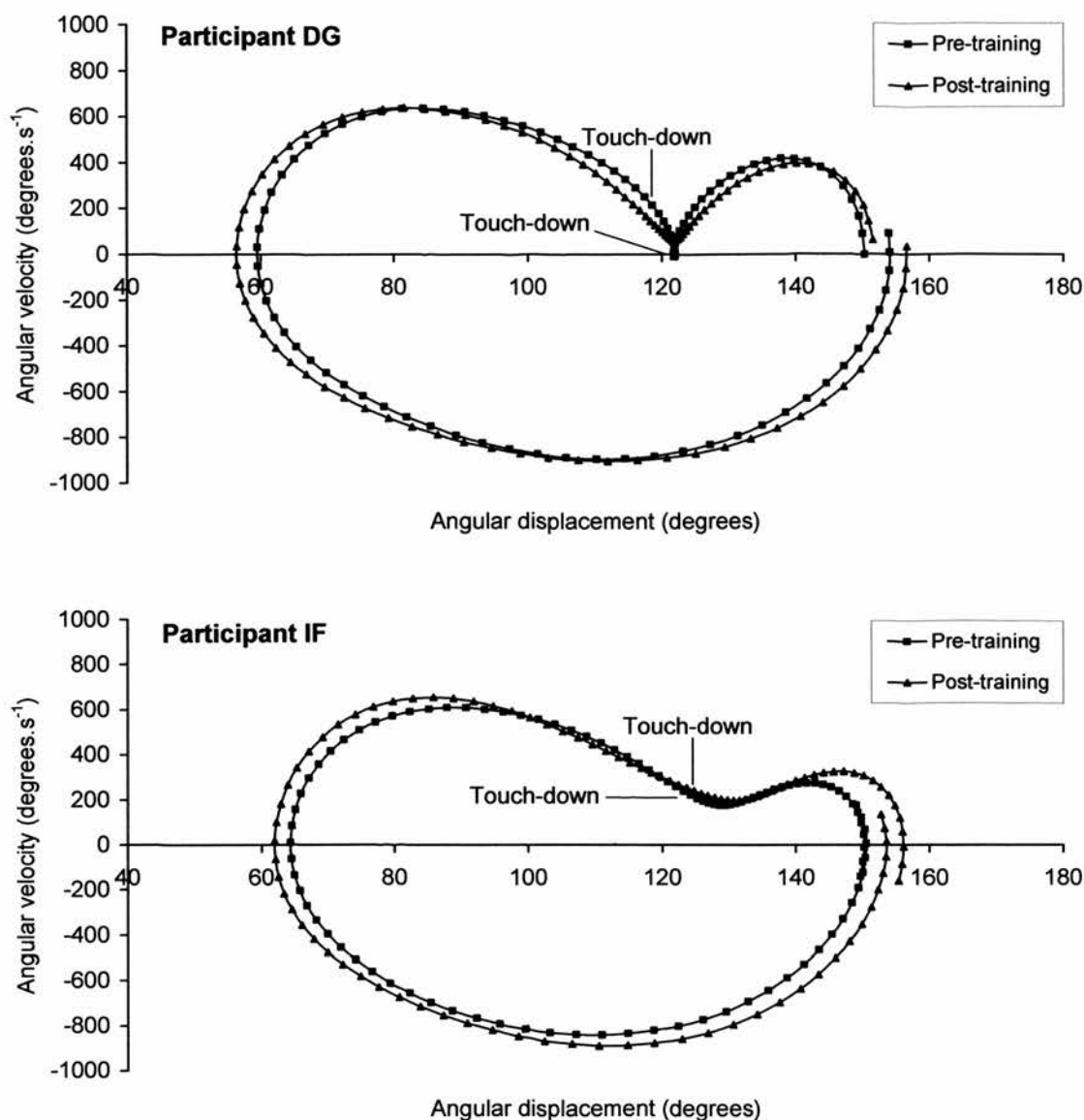
All participants, with the exception of KL, increased the extension about the hip at touch-down across the testing sessions, although the increases by the 'increase responders' (AD = 10°; IF = 7°) were greater than that for participant AD (4°). Participant KL reduced extension about the hip joint at touch-down post-training. At toe-off all participants, with the exception of KL, increased the extension about the hip joint post-training, although the increases for the 'increase responders' (DG = 4°; IF = 6°) were less than that for participant AD (8°). Participant KL slightly reduced extension about the knee at toe-off post-training. However, given the reduction in knee extension at touch-down this participant actually increased the RoM about the hip joint during the stance period, as did participant AD. Despite the increase in hip extension at toe-off, the 'increase responders' reduced the RoM about the hip joint during stance post-training due to the greater increases in hip extension at touch-down.

The phase-plane diagrams of the knee joint during stride 1 for the 'maintenance' and 'increase' responders are shown in Figures 5.9 and 5.10, respectively. All participants increased the RoM about the knee joint following the resistance training intervention due to an increase in extension at the beginning of the stride cycle and an increase in flexion during the flight period. With the exception of AD, all participants increased the extension about the knee at touch-down during the post-training testing session. Participant AD touched down with a greater angle of knee flexion post-training, but actually increased the RoM during stance as the angle of extension was unchanged across the testing sessions. All of the other participants increased extension at toe-off following the resistance training intervention, although participant DG did not increase the RoM about the knee during the stance period. This participant also decreased the angular velocity of extension following touch-down to zero during the post-training testing session. Despite these changes, all participants maintained the temporal behaviour of the knee joint following the resistance training intervention.





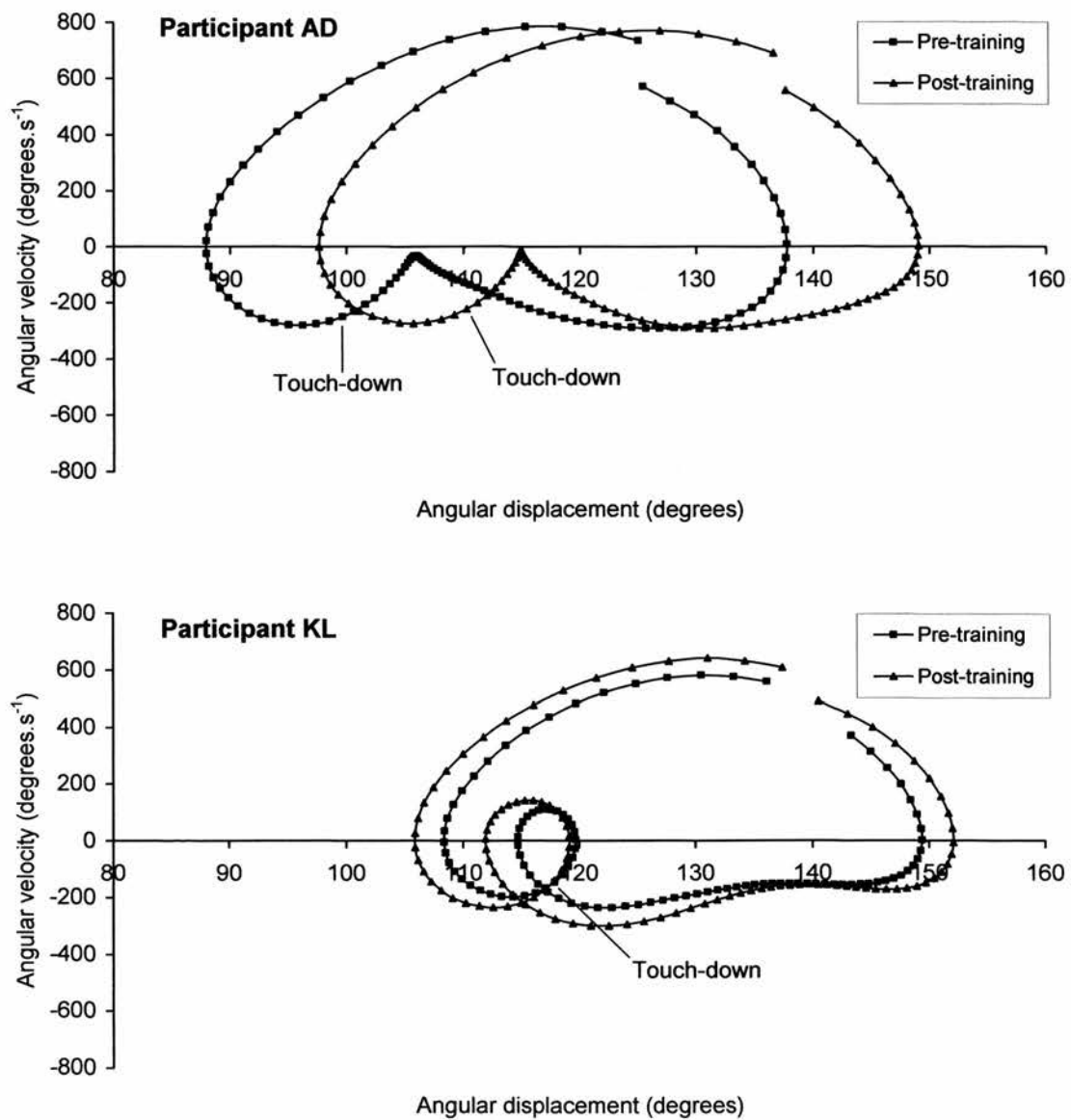
**Figure 5.9** Pre and post-training phase-plane diagrams of the knee joint during stride 1 for two 'maintenance responders' from the experimental group. Values are means. Note: Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.



**Figure 5.10** Pre and post-training phase-plane diagrams of the knee joint during stride 1 for two 'increase responders' from the experimental group. Values are means. Note: Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

The ankle phase-plane diagrams for the 'maintenance' and 'increase' responders are shown in Figures 5.11 and 5.12, respectively. All participants began the stride cycle with greater plantar flexion following the resistance training intervention. Similarly, all participants began the stance period with a greater angle of plantar flexion post-training, with the exception of participant KL who touched-down at the same angle during the pre and post-training strides. Although all participants increased the angle of plantar flexion about the ankle joint at toe-off at the end of the stride cycle during the post-training testing session

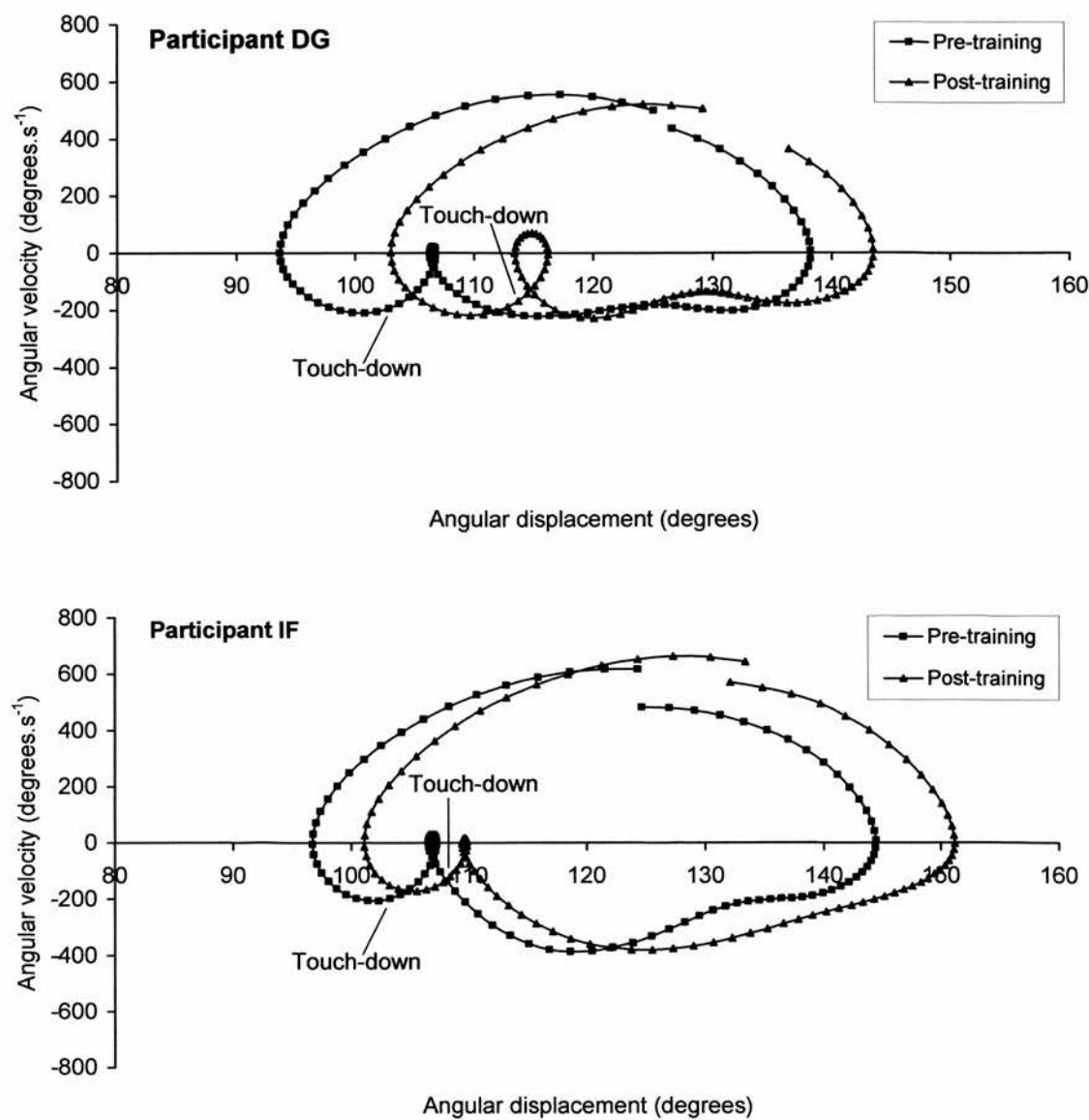
(Figures 5.11 & 5.12), because of the changes in the ankle angle at touch-down only participant AD substantially increased the RoM about the ankle during stance. Indeed, participant DG actually reduced the RoM about the ankle joint following the resistance training intervention.



**Figure 5.11** Pre and post-training phase-plane diagrams of the ankle joint during stride 1 for two 'maintenance responders' from the experimental group. Values are means. Note: Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.

Participant AD maintained the temporal characteristics of the behaviour about the ankle joint across the testing sessions, with particular events (e.g. plantar flexion-dorsi flexion

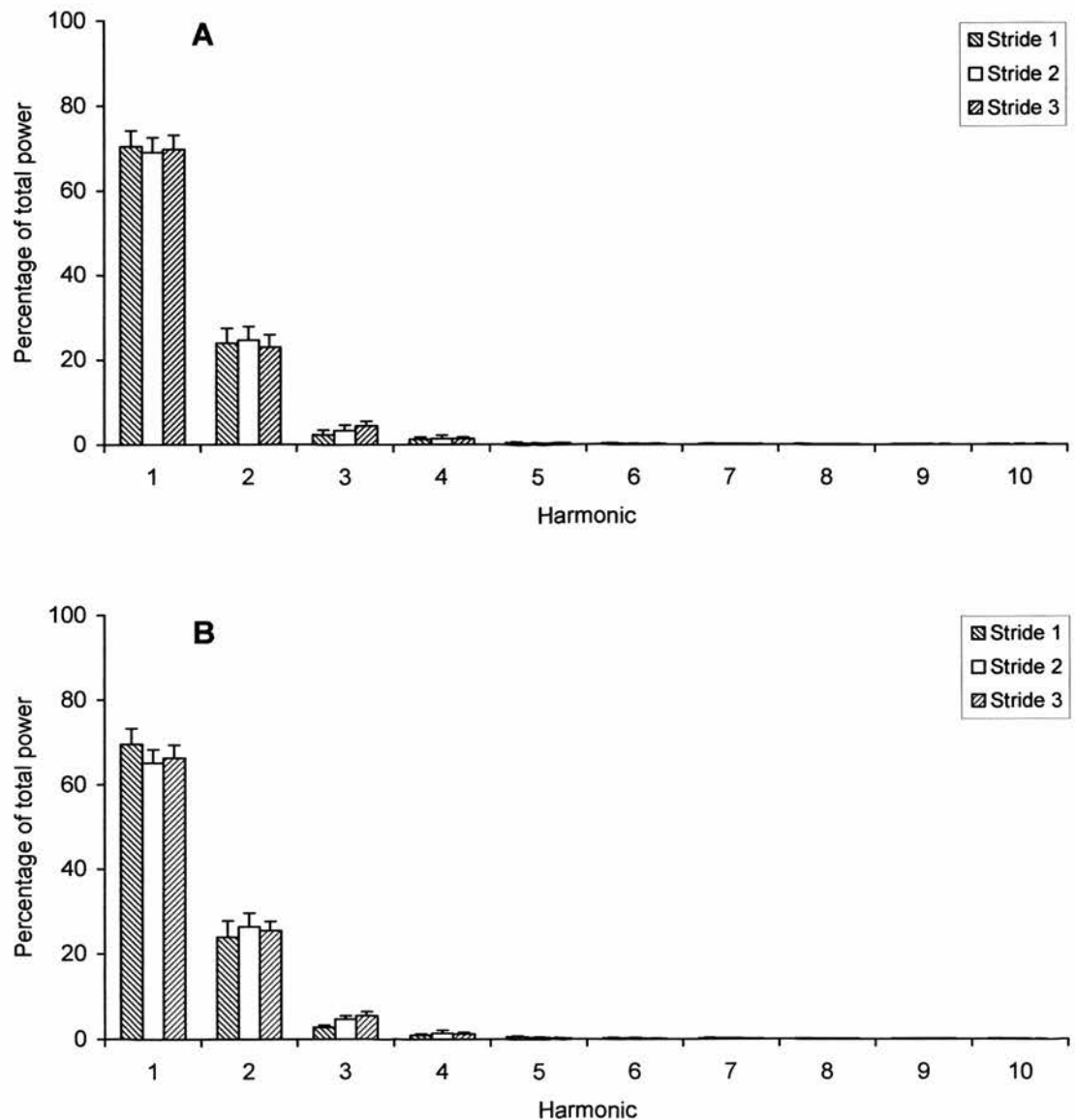
transition) occurring at different displacement values (Figure 5.11). However, following the resistance training intervention participant KL delayed the transition from plantar flexion to dorsi flexion early in the stride cycle. Conversely, both ‘increase responders’ expedited this transition post-training (Figure 5.12). Despite these changes early during the stride cycle, there were no temporal changes at touch-down for these participants.



**Figure 5.12** Pre and post-training phase-plane diagrams of the ankle joint during stride 1 for two ‘increase responders’ from the experimental group. Values are means. Note: Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

5.14 Spectral analysis

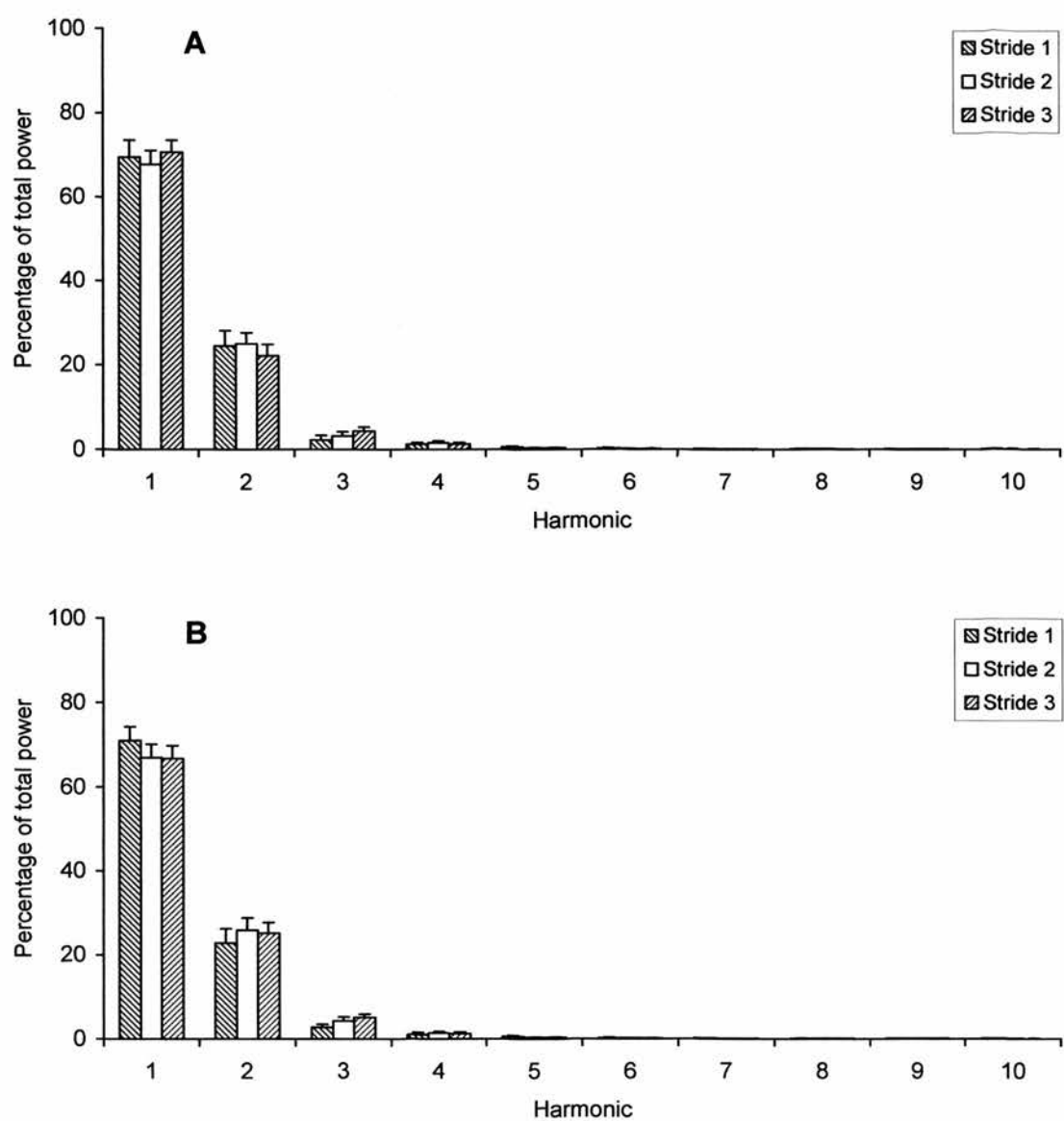
Exemplar power spectra for the knee angular displacement signal during the first 3 strides of the 20 m sprint for the experimental and control groups recorded pre and post-training are shown in Figures 5.13 and 5.14, respectively. The percent power contained within each harmonic for the pre-training values are typical of the spectra for the other joints.



**Figure 5.13** Pre-training power spectrum for the angular displacement signal for the knee joint during the first 3 strides of the 20 m sprint for the experimental (A) and control (B) groups. Values are means; bars are standard deviations.

In the pre-training power spectra (Figure 5.13) the majority of the power (approximately 70%) was contained within the first harmonic for all 3 strides in both groups, with just over

20% of the power contained within the second harmonic. For the experimental group the fundamental frequency corresponded to  $2.15 \pm 0.18$  Hz for stride 1,  $2.22 \pm 0.20$  Hz for stride 2 and  $2.26 \pm 0.21$  Hz for stride 3. The corresponding values for the control group were  $2.02 \pm 0.19$  Hz,  $2.12 \pm 0.14$  Hz and  $2.14 \pm 0.14$  Hz for strides 1, 2 and 3, respectively.

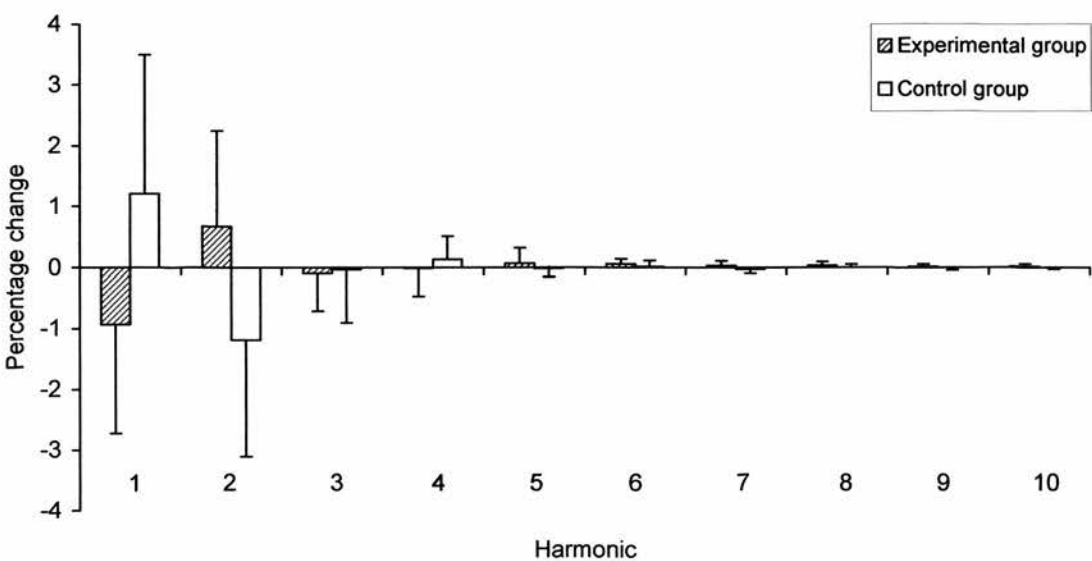


**Figure 5.14** Post-training power spectrum for the angular displacement signal for the knee joint during the first 3 strides of the 20 m sprint for the experimental (A) and control (B) groups. Values are means; bars are standard deviations.

The post-training power spectrum for the knee angular displacement signal for both groups (Figure 5.14) shows the majority of the power was contained within the first harmonic for all 3 strides in both groups. For the experimental group the fundamental frequency

corresponded to  $2.09 \pm 0.19$  Hz for stride 1,  $2.18 \pm 0.19$  Hz for stride 2 and  $2.20 \pm 0.21$  Hz for stride 3 with the corresponding values for the control group of  $2.00 \pm 0.19$  Hz,  $2.08 \pm 0.17$  Hz and  $2.12 \pm 0.14$  Hz for strides 1, 2 and 3, respectively.

Analysis of the change in the percentage of total power within the first 10 harmonics for the angular displacement signal of the knee joint revealed a significant group x testing occasion interaction during stride 2 ( $F(1.33, 19.94) = 4.29, P = 0.042$ ). Repeated contrasts revealed significant differences between harmonics 1 and 2 ( $F(1, 15) = 5.01, P = 0.041$ ) and between harmonics 2 and 3 ( $F(1,15) = 4.59, P = 0.049$ ) with the experimental group tending to shift power towards the higher harmonics following the resistance training intervention and the control group shifting power to the lower harmonics (Figure 5.15). There were no other significant main effects or interactions for the angular displacement signals of the other joints during the first 3 strides.



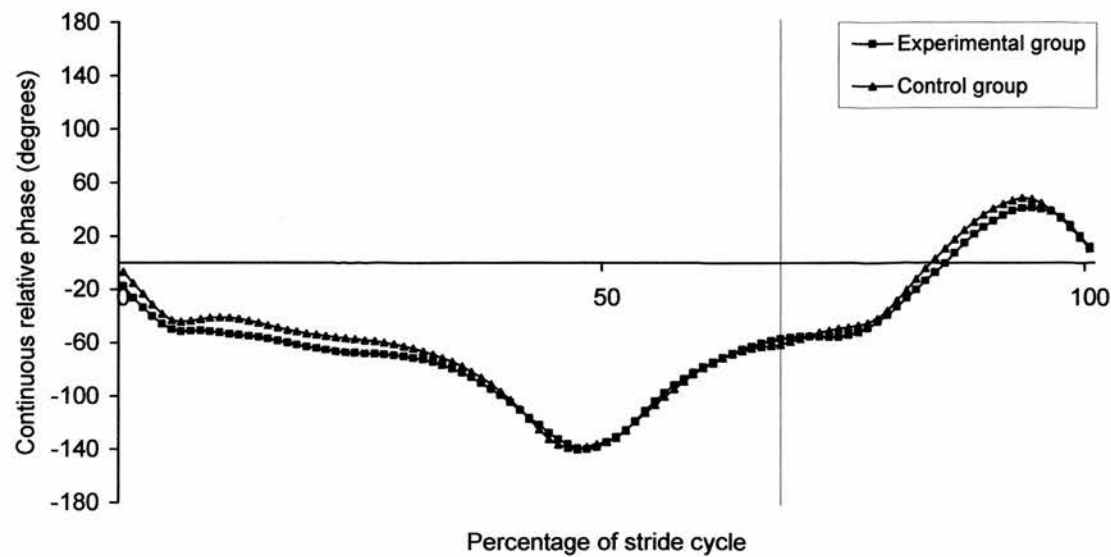
**Figure 5.15** Percentage change in the first 10 harmonics for the knee angular displacement signal during stride 2 of the 20 m sprint for the experimental and control groups. Values are means; bars are standard deviations.

### 5.15 Relative phase measures

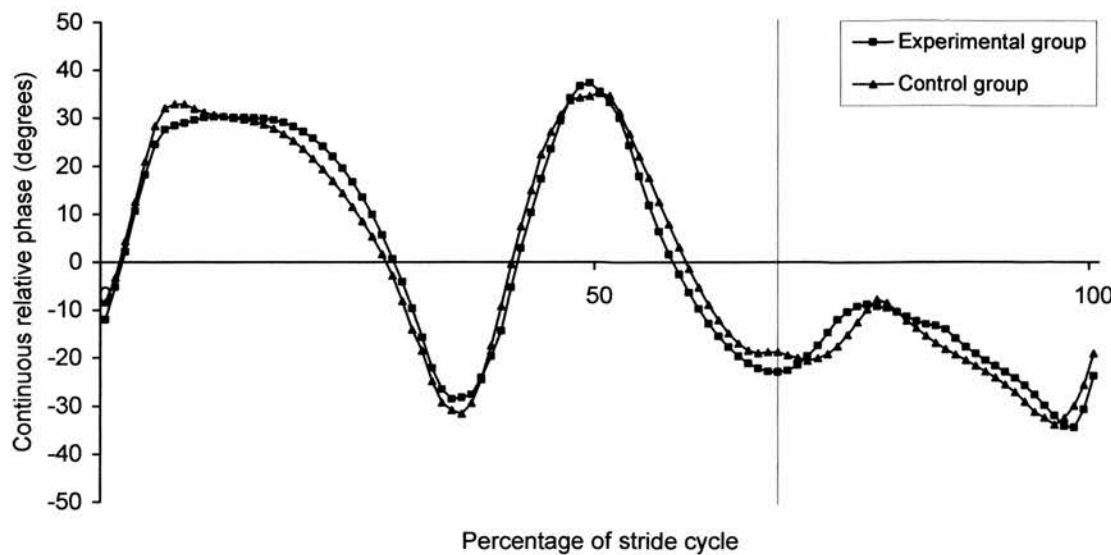
Exemplar mean continuous relative phase (CRP) graphs for the shoulder-hip, hip-knee and knee-ankle joint couplings are shown in Figures 5.16, 5.17 and 5.18, respectively. Each graph depicts the mean ensemble pre-training CRP for the experimental and control groups during stride 1. The mean curves were calculated by combining the data from all of the



participants in the two respective groups. The graphs cover an entire stride cycle from toe-off (0%) to next ipsilateral toe-off (100%).

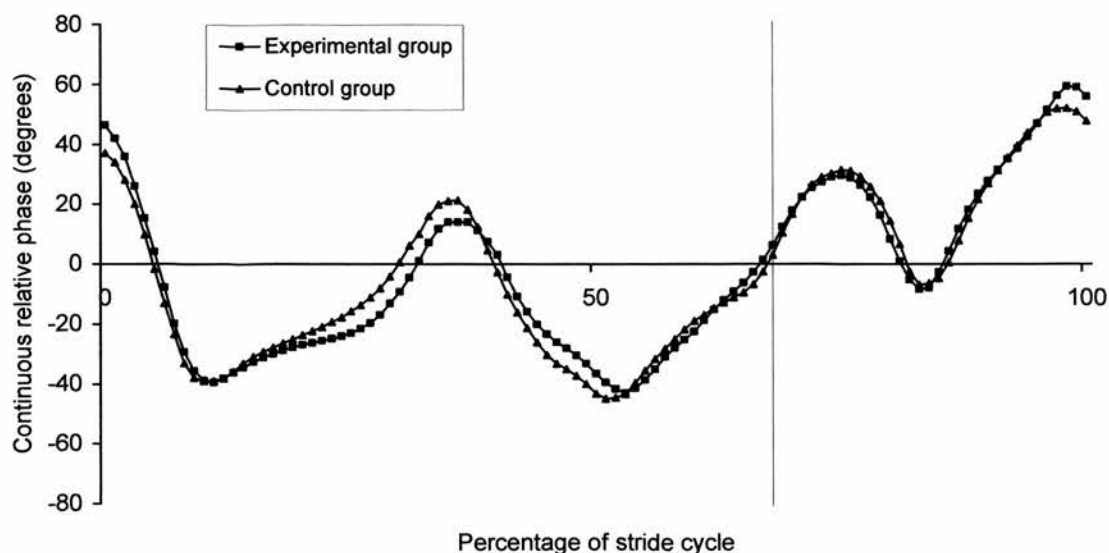


**Figure 5.16** Pre-training continuous relative phase for the shoulder-hip joint coupling during stride 1 of the 20 m sprint for the experimental and control groups. Values are means. Note: The vertical line crossing the abscissa indicates touch-down.



**Figure 5.17** Pre-training continuous relative phase for the hip-knee joint coupling during stride 1 of the 20 m sprint for the experimental and control groups. Values are means. Note: The vertical line crossing the abscissa indicates touch-down.

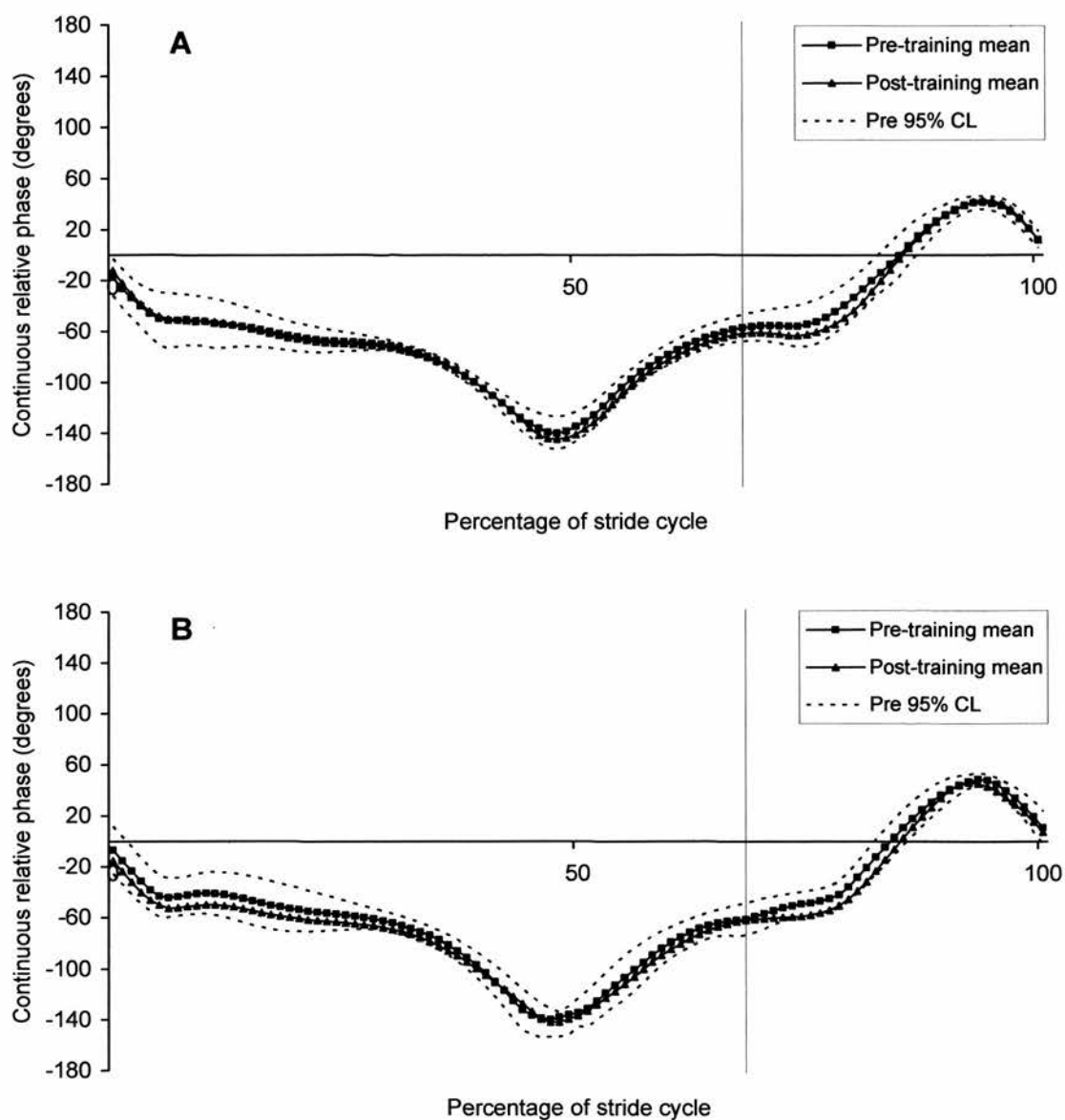
The pre-training CRP graphs for the shoulder-hip joint coupling for both the experimental and control groups (Figure 5.16) following very similar patterns. For the first half of the stride cycle the two joints move progressively out of phase, following which the relationship moves towards in-phase. Figure 5.17 shows the pre-training CRP graphs for the hip-knee joint coupling for both groups. The patterns for each group are very similar with six reversals in the co-ordination between the joints during the stride cycle. Despite these reversals, the hip and knee joints maintain a relatively in-phase relationship across the stride cycle.



**Figure 5.18** Pre-training continuous relative phase for the knee-ankle joint coupling during stride 1 of the 20 m sprint for the experimental and control groups. Values are means. Note: The vertical line crossing the abscissa indicates touch-down.

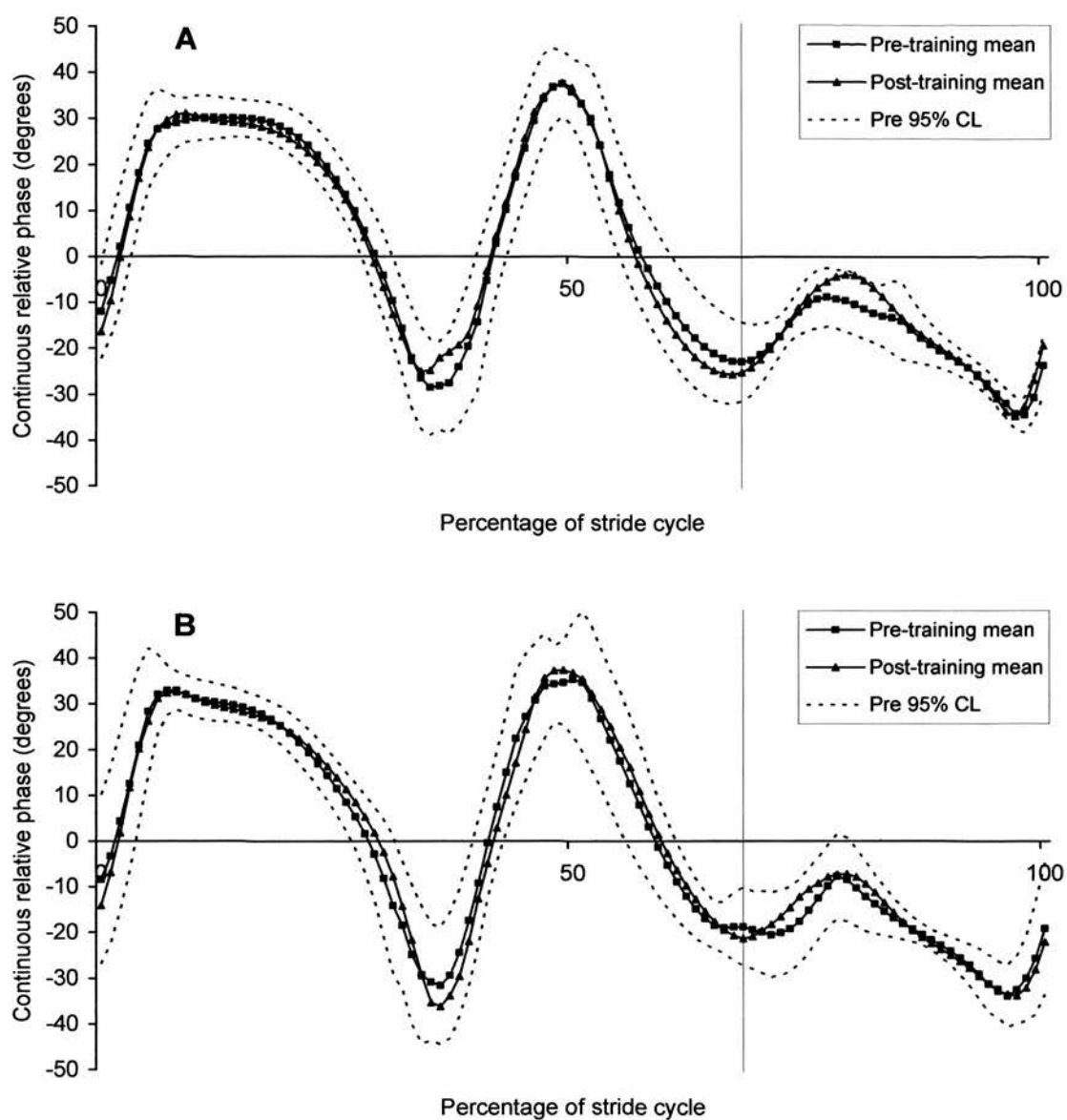
The pre-training knee-ankle CRP graphs for the experimental and control groups are shown in Figure 5.18. As with the other joint couplings, the pre-training knee-ankle CRP for both groups follow very similar patterns. As with the hip-knee CRP the knee and ankle joints maintain a relatively in-phase relationship across the entire stride cycle despite the reversals in co-ordination during the stride.

Exemplar graphs of the mean ensemble pre and post-training shoulder-hip, hip-knee and knee-ankle CRP for the experimental and control groups are shown in Figures 5.19, 5.20 and 5.21, respectively. The graphs are shown for the joint couplings during stride 1 and also display the pre-training 95% confidence limits of the true mean for each group.

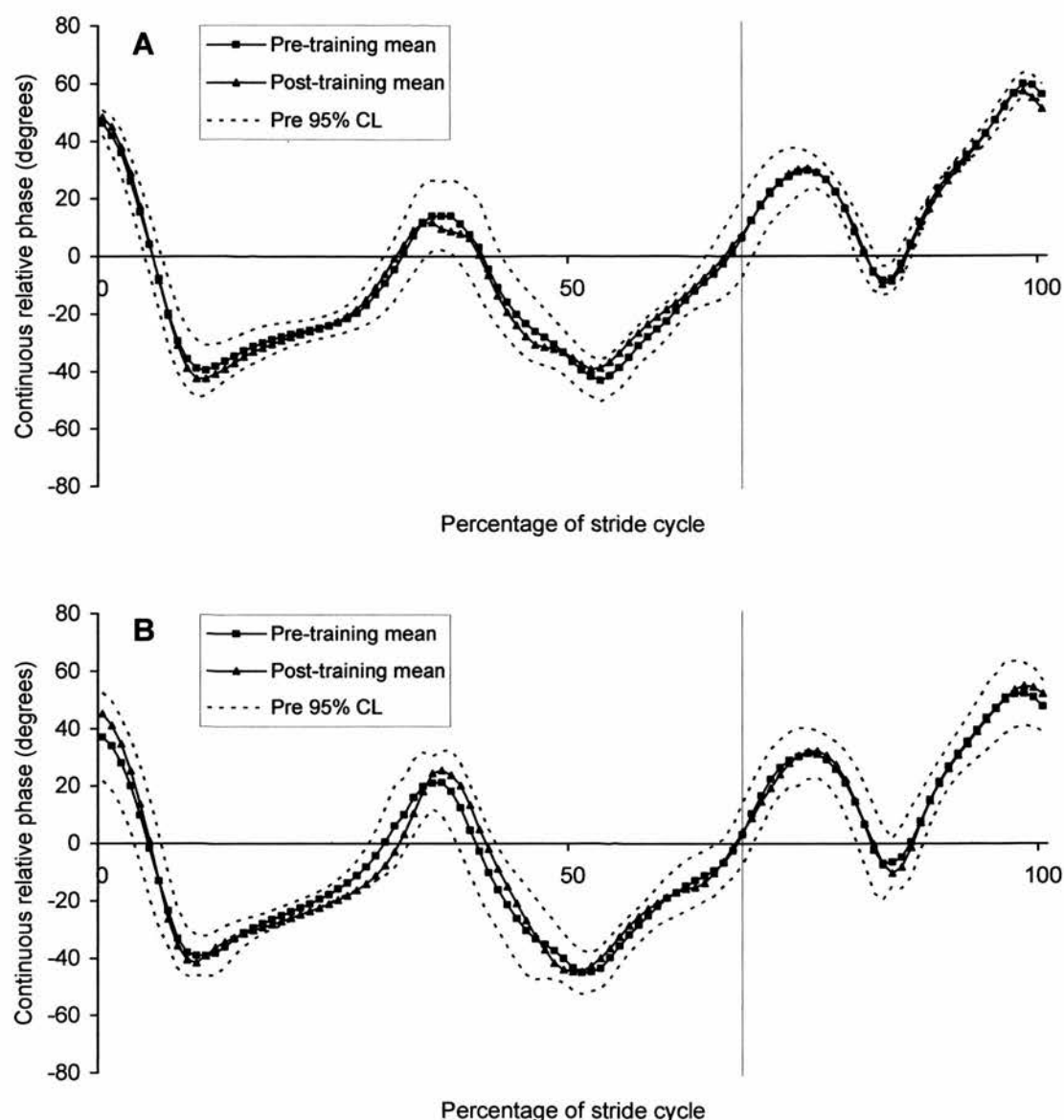


**Figure 5.19** Pre and post-training shoulder-hip continuous relative phase and associated 95% confidence limits during stride 1 of the 20 m sprint for the experimental (A) and control (B) groups. Only the pre-training confidence limits for each group are shown for clarity. Note: The vertical line crossing the abscissa indicates touch-down. CL = confidence limits.

The post-training mean graphs for both the experimental and control groups fall within the pre-training confidence limits for all of the CRP measures. The absence of any substantial changes in the joint relationships depicted in these graphs for either group was typical across strides 2 and 3.



**Figure 5.20** Pre and post-training hip-knee continuous relative phase and associated 95% confidence limits during stride 1 of the 20 m sprint for the experimental (A) and control (B) groups. Only the pre-training confidence limits for each group are shown for clarity. Note: The vertical line crossing the abscissa indicates touch-down. CL = confidence limits.



**Figure 5.21** Pre and post-training knee-ankle continuous relative phase and associated 95% confidence limits during stride 1 of the 20 m sprint for the experimental (A) and control (B) groups. Only the pre-training confidence limits for each group are shown for clarity. Note: The vertical line crossing the abscissa indicates touch-down. CL = confidence limits.

The correlation coefficients between the pre-post shoulder-hip, hip-knee and knee-ankle CRP graphs for both groups during the first 3 strides of the 20 m sprint were all large ( $r \geq 0.93$ ). Independent t-tests performed on the correlation coefficients following Fisher Z-transformation revealed no significant differences between the groups ( $P > 0.05$ ), indicating strong associations between the pre and post-training CRP graphs for both groups.

The pre and post-training absolute mean CRP for the shoulder-hip, hip-knee and knee-ankle couplings during the first 3 strides of the 20 m sprint for the experimental and control groups are shown in Table 5.8.

**Table 5.8** Pre and post-training absolute mean continuous relative phase values during the first 3 strides of the 20 m sprint. Values are means  $\pm$  standard deviations.

Stride	Group	Continuous relative phase coupling					
		Shoulder-hip (degrees)		Hip-knee (degrees)		Knee-ankle (degrees)	
		Pre	Post	Pre	Post	Pre	Post
Stride 1	Exp	65.82	67.97	22.32	22.03	26.92	27.13
		$\pm 9.64$	$\pm 6.76$	$\pm 2.83$	$\pm 2.35$	$\pm 2.70$	$\pm 2.57$
	Con	62.75	62.75	22.22	21.90	25.96	26.32
		$\pm 7.04$	$\pm 7.04$	$\pm 2.04$	$\pm 1.68$	$\pm 3.62$	$\pm 2.97$
Stride 2	Exp	63.39	65.33	24.46	24.59	29.11	29.01
		$\pm 10.52$	$\pm 6.71$	$\pm 2.14$	$\pm 2.25$	$\pm 3.06$	$\pm 3.02$
	Con	61.75	65.22	24.02	24.14	27.61	28.43
		$\pm 1.87$	$\pm 5.05$	$\pm 1.83$	$\pm 1.52$	$\pm 2.55$	$\pm 2.36$
Stride 3	Exp	63.12	64.91	25.26	25.50	28.32	28.40
		$\pm 8.55$	$\pm 6.50$	$\pm 1.45$	$\pm 1.64$	$\pm 4.17$	$\pm 3.77$
	Con	61.62	66.44	24.70	24.03	27.51	27.77
		$\pm 4.23$	$\pm 4.78$	$\pm 2.55$	$\pm 2.44$	$\pm 3.01$	$\pm 2.76$

Note: Pre = pre-training; Post = post-training; Exp = experimental group; Con = control group.

There was a significant main effect for testing occasion for the shoulder-hip absolute mean CRP during strides 1, 2 and 3 (Table 5.9). Both groups tended to increase absolute mean CRP across the two testing sessions (Stride 1 – mean difference between testing sessions:  $3.26^\circ$ ; 95% likely range:  $1.47^\circ - 5.05^\circ$ . Stride 2 – mean difference between testing sessions:  $2.70^\circ$ ; 95% likely range:  $0.15^\circ - 5.25^\circ$ . Stride 3 –  $3.31^\circ$ ; 95% likely range:  $1.48^\circ - 5.14^\circ$ ). There were no other significant main effects or interactions for any of the other absolute mean CRP joint couplings during the first 3 strides of the 20 m sprint.

**Table 5.9** Results of the ANOVA performed on the absolute mean continuous relative phase values for the shoulder-hip joint couplings during the first 3 strides of the 20 m sprint. Main effects and interactions are shown.

Stride	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Stride 1	15.08	0.001	0.27	0.609	1.74	0.207
Stride 2†	5.11	0.039	0.07	0.799	0.41	0.533
Stride 3	14.87	0.002	0.00	0.996	3.12	0.097

Note: \* 1, 15 degrees of freedom; † Levene's test for equality of error variances for the pre-training values ( $F(1,15) = 6.844$ ,  $P = 0.019$ ).

There were significant main effects for testing occasion for the shoulder-hip discrete relative phase (RP) at touch-down during strides 2 and 3 (Table 5.10). These main effects were caused by both groups increasing the RP across the testing sessions during stride 2 (mean difference between testing sessions:  $8.05^\circ$ ; 95% likely range:  $2.25^\circ - 13.85^\circ$ ) and stride 3 (mean difference between testing sessions:  $6.73^\circ$ ; 95% likely range:  $1.58^\circ - 11.89^\circ$ ). There were no other significant main effects or interactions for the measures of discrete RP at touch-down or toe-off for the shoulder-hip, hip-knee or knee-ankle joint couplings ( $P > 0.05$ ).

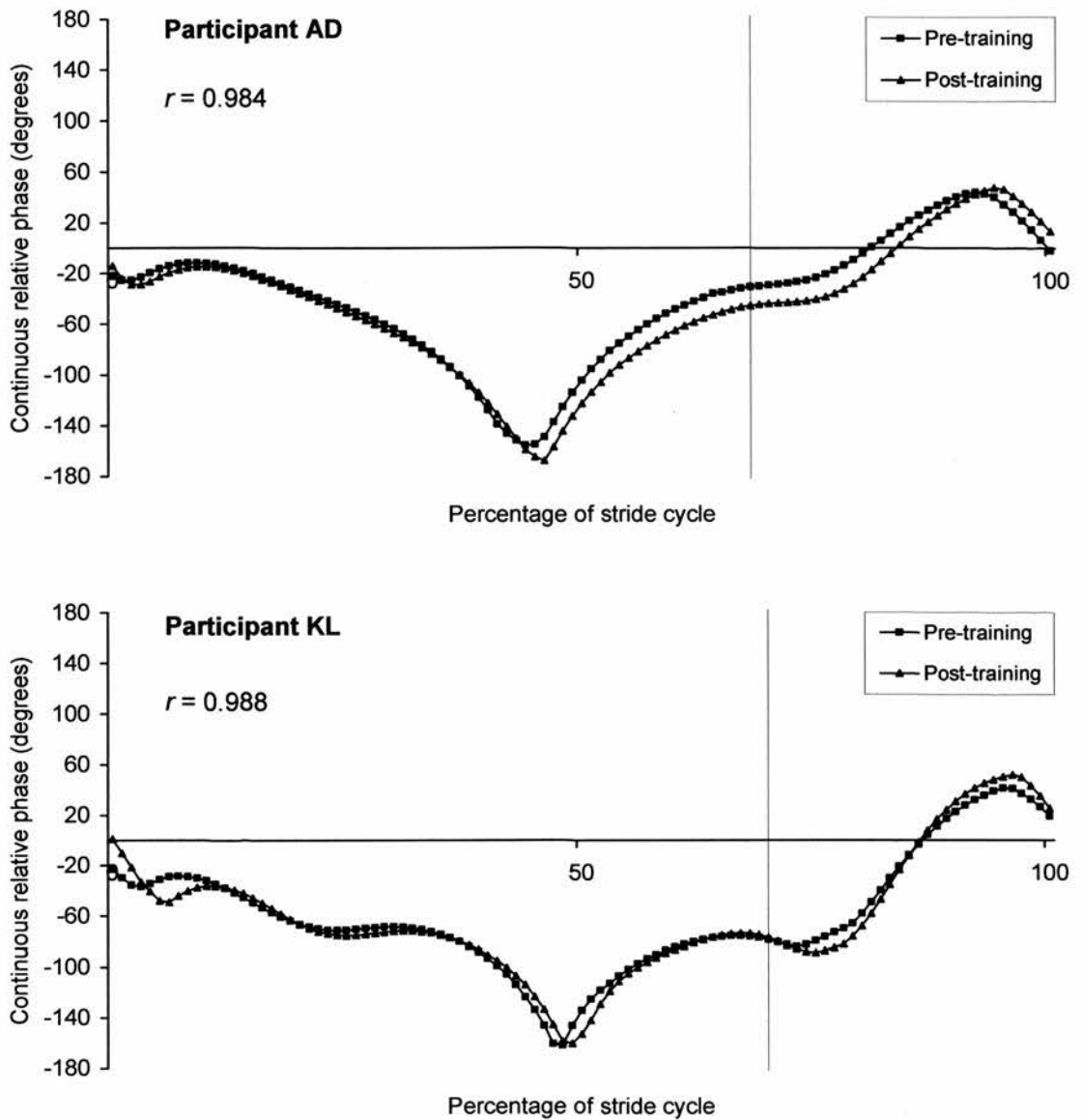
**Table 5.10** Results of the ANOVA performed on the discrete relative phase values for the shoulder-hip joint couplings at touch-down during the first 3 strides of the 20 m sprint. Main effects and interactions are shown.

Stride	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Stride 1	4.22	0.058	0.00	0.998	0.73	0.407
Stride 2†	8.75	0.010	0.01	0.909	0.60	0.451
Stride 3	7.75	0.014	0.40	0.538	0.34	0.567

Note: \* 1, 15 degrees of freedom. † Levene's test for equality of error variances for the pre-training values ( $F(1,15) = 6.38$ ,  $P = 0.023$ ).

Figures 5.22 through to 5.27 show the mean ensemble CRP graphs for the shoulder-hip, hip-knee and knee-ankle joint couplings during stride 1 for the 'maintenance' and 'increase' responders from the experimental group. The relationships shown in these graphs are typical of those for strides 2 and 3.

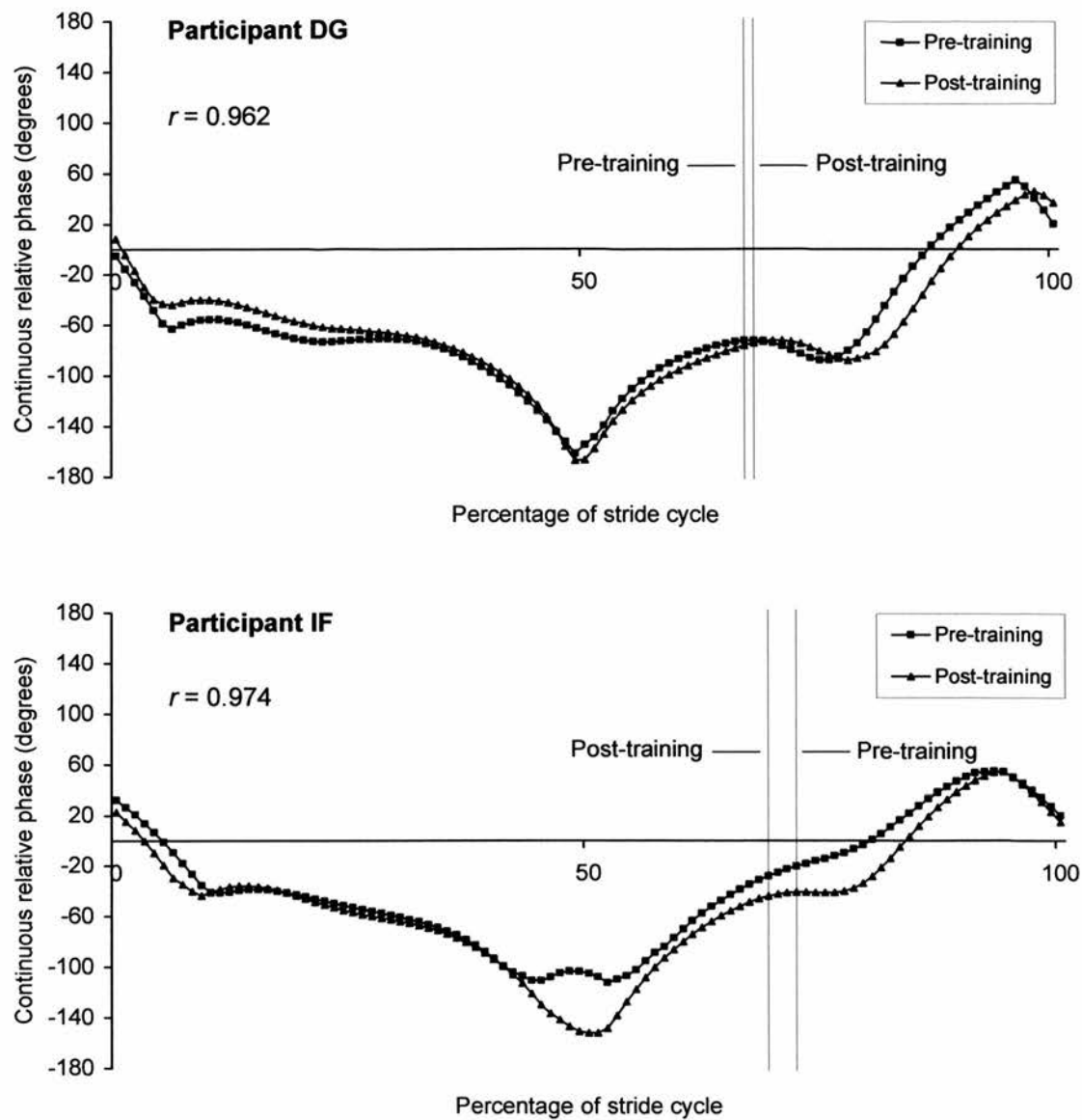




**Figure 5.22** Pre and post-training shoulder-hip continuous relative phase during stride 1 for two 'maintenance responders' from the experimental group. Values are means. Note: The vertical line crossing the abscissa indicates touch-down. The correlation coefficient ( $r$ ) between the pre and post-training graphs is shown. Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.

Figures 5.22 and 5.23 show the mean ensemble CRP graphs for the shoulder-hip joint couplings. The large correlation coefficients for all participants indicate strong associations between the pre and post-training graphs. The increase in the relative phase at touch-down post-training for participant AD (Figure 5.22) was caused by a large increase in the extension about the shoulder joint at this time, while the change at the beginning of the stride cycle for

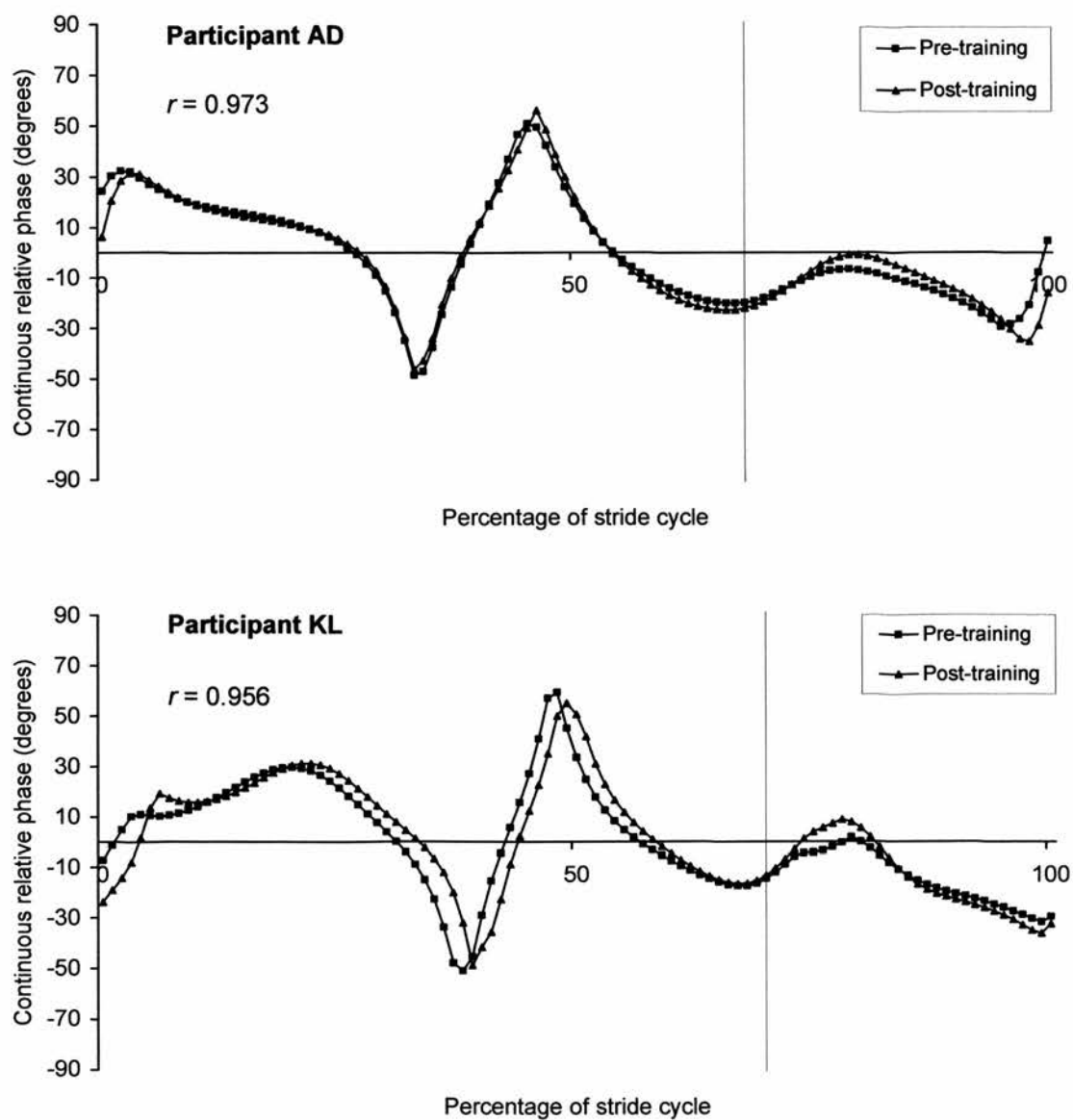
participant KL was caused by the greater angular velocity (extension) about the hip joint post-training.



**Figure 5.23** Pre and post-training shoulder-hip continuous relative phase during stride 1 for two ‘increase responders’ from the experimental group. Values are means. Note: The vertical lines crossing the abscissa indicate touch-down. The correlation coefficient ( $r$ ) between the pre and post-training graphs is shown. Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

For participant IF (Figure 5.23) the difference in the shoulder-hip mean ensemble CRP graphs at 50% of the stride cycle was due to the post-training increase in extension about the

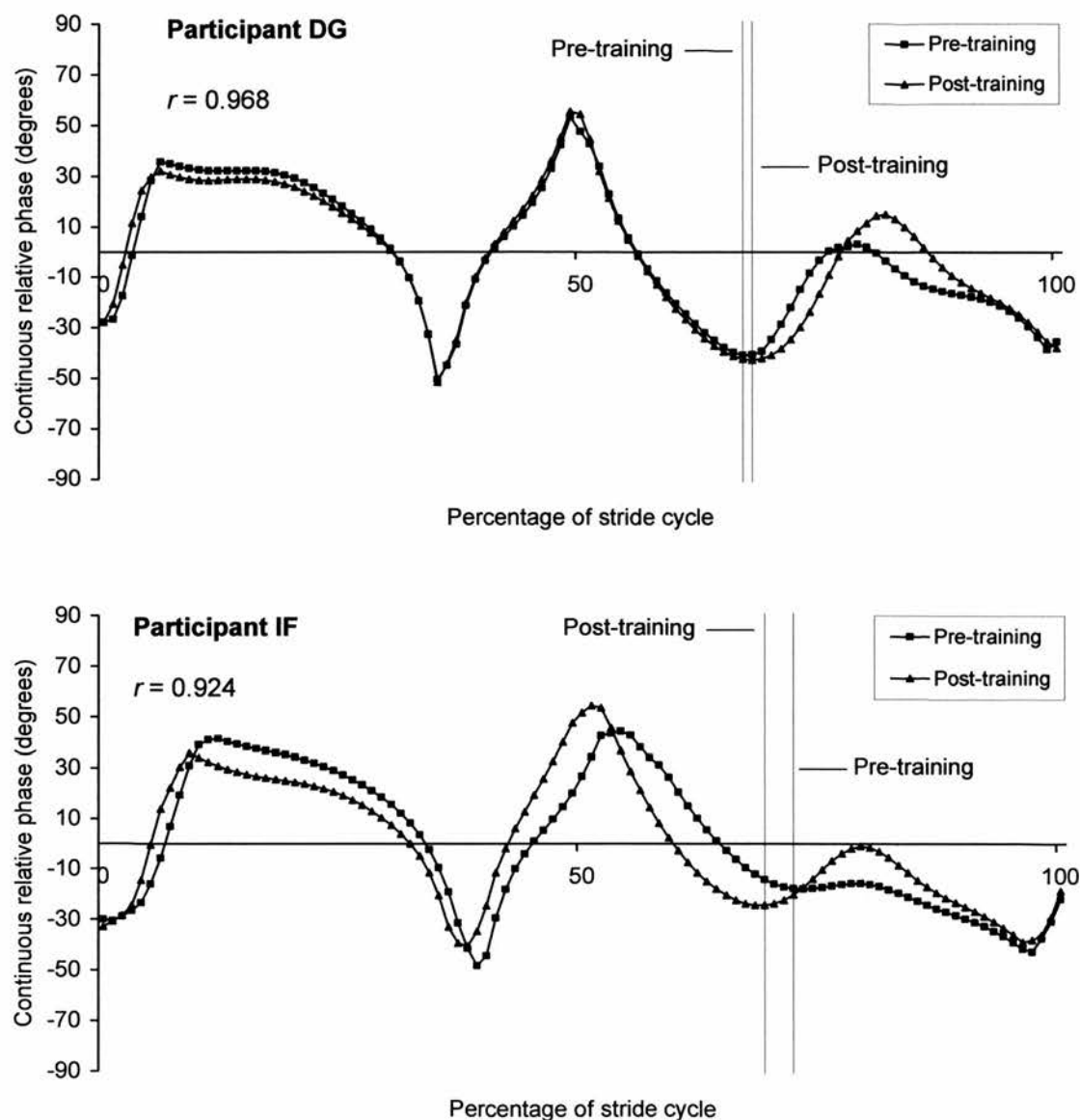
shoulder joint, while the post-training increase in negative relative phase at touch-down was also caused by the large post-training increase in shoulder extension.



**Figure 5.24** Pre and post-training hip-knee continuous relative phase during stride 1 for two ‘maintenance responders’ from the experimental group. Values are means. Note: The vertical line crossing the abscissa indicates touch-down. The correlation coefficient ( $r$ ) between the pre and post-training graphs is shown. Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.

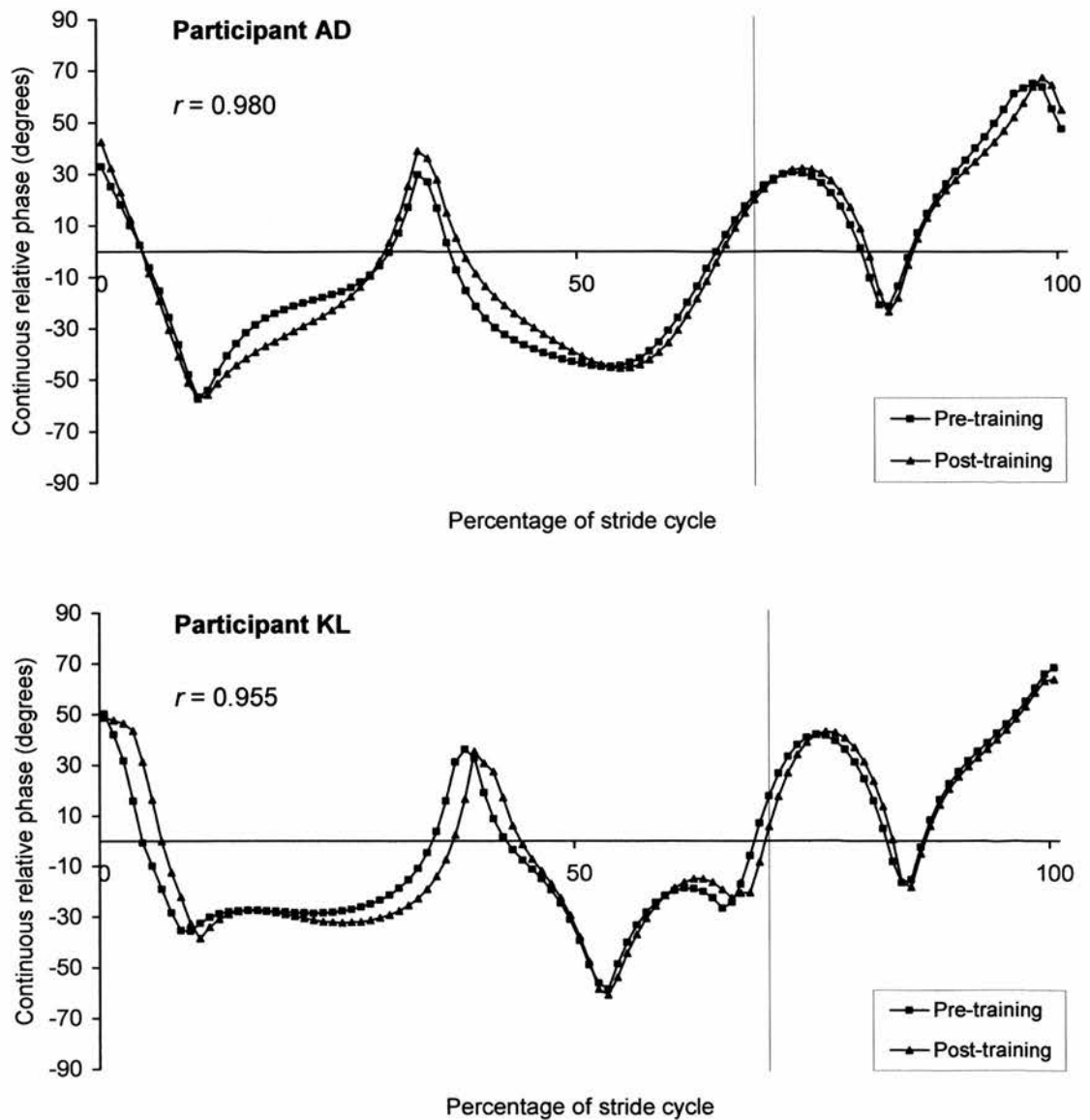
Figures 5.24 and 5.25 show the pre and post-training mean ensemble hip-knee CRP graphs for the ‘maintenance’ and ‘increase’ responders from the experimental group. There were strong associations between the pre and post-training graphs for all participants. However, participant IF (Figure 5.25) demonstrated post-training alterations in the hip-knee coupling

during the flight period. These differences were caused by the temporal changes about the hip joint (see Figure 5.8). Despite these differences, at touch-down the relative phase between the hip and knee joints was very similar across the two testing sessions.



**Figure 5.25** Pre and post-training hip-knee continuous relative phase during stride 1 for two 'increase responders' from the experimental group. Values are means. Note: The vertical lines crossing the abscissa indicate touch-down. The correlation coefficient ( $r$ ) between the pre and post-training graphs is shown. Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

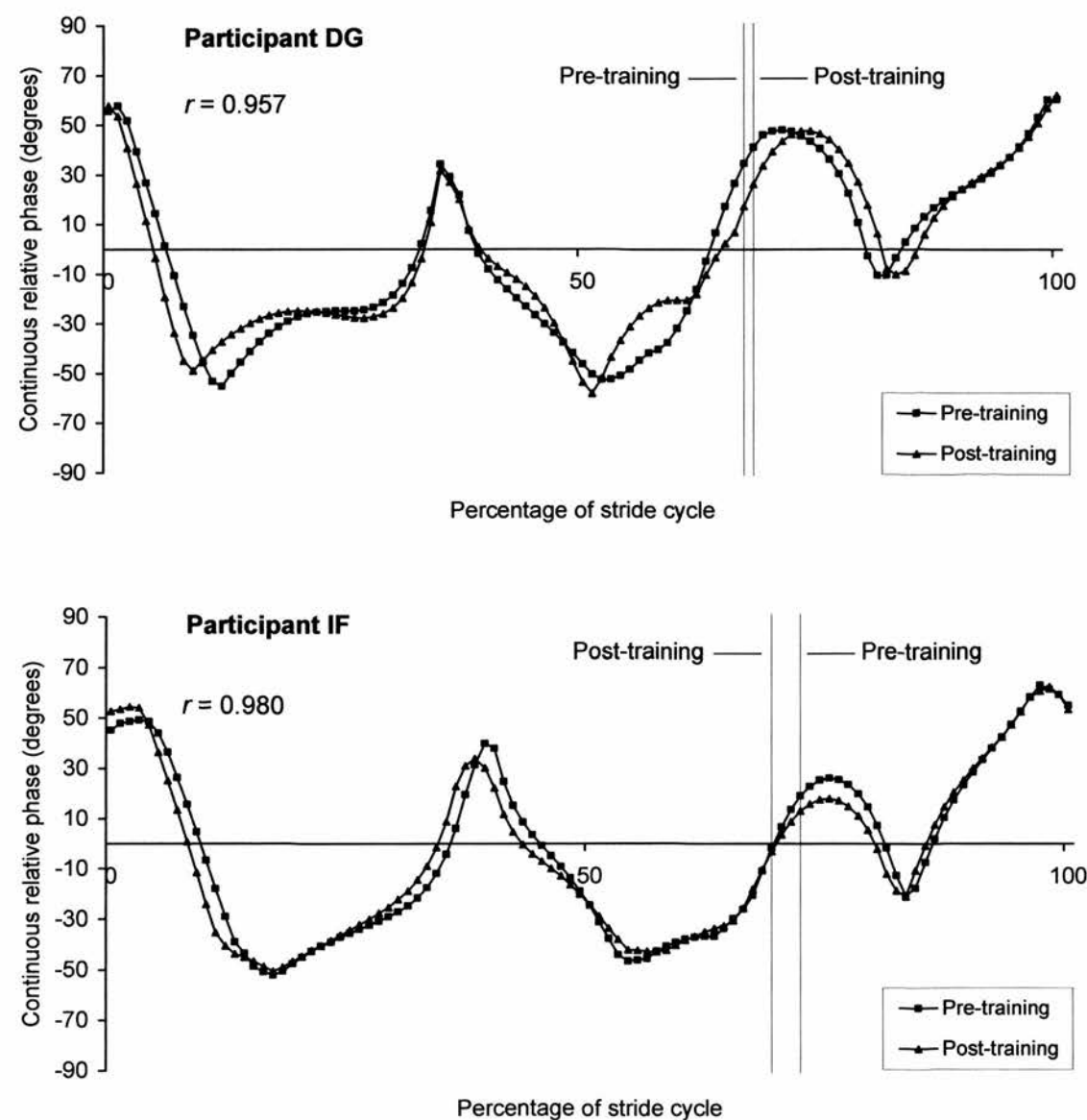
Conversely, the hip-knee joint coupling for participant DG was unaltered during the flight period and at touch-down (Figure 5.25). However, during the stance period there were changes post-training, caused by the temporal alterations about the hip joint (see Figure 5.8).



**Figure 5.26** Pre and post-training knee-ankle continuous relative phase during stride 1 for two ‘maintenance responders’ from the experimental group. Values are means. Note: The vertical line crossing the abscissa indicates touch-down. The correlation coefficient ( $r$ ) between the pre and post-training graphs is shown. Participant AD increased 10 m time by 1%; participant KL increased 10 m time by 2%.

Figures 5.26 and 5.27 show the pre and post-training CRP graphs for the knee-ankle joint coupling from the ‘maintenance’ and ‘increase’ responders to the resistance training

intervention. Although the correlation coefficients suggest strong associations between the pre and post-training graphs for all participants, there are some notable changes, particularly for the ‘increase responders’ (Figure 5.27). For example, at touch-down there was a post-training decrease in the positive relative phase for participant DG which was caused by an increase in plantar flexion about the ankle joint (see Figure 5.12).



**Figure 5.27** Pre and post-training knee-ankle continuous relative phase during stride 1 for two ‘increase responders’ from the experimental group. Values are means. Note: The vertical lines crossing the abscissa indicate touch-down. The correlation coefficient ( $r$ ) between the pre and post-training graphs is shown. Participant DG increased 10 m time by 14%; participant IF increased 10 m time by 9%.

A similar increase in plantar flexion at touch-down caused the relative phase between the knee and the ankle to change from positive to negative following the resistance training intervention for participant IF (Figure 5.27).

### 5.16 Continuous relative phase variability

Table 5.11 shows the group means for the pre and post-training root mean square error (RMSE) calculated for the CRP measures during the first 3 strides of the 20 m sprint.

**Table 5.11** Pre and post-training continuous relative phase variability during the first 3 strides of the 20 m sprint. Values are means  $\pm$  standard deviations.

Stride	Group	Continuous relative phase coupling					
		Shoulder-hip (degrees)		Hip-knee (degrees)		Knee-ankle (degrees)	
		Pre	Post	Pre	Post	Pre	Post
Stride 1	Exp	14.25	10.30	10.93	9.08	12.69	12.43
		$\pm 4.94$	$\pm 2.65$	$\pm 1.55$	$\pm 2.25$	$\pm 1.26$	$\pm 4.90$
	Con	14.43	13.88	8.67	9.25	12.66	11.52
		$\pm 6.19$	$\pm 6.43$	$\pm 2.55$	$\pm 1.39$	$\pm 2.24$	$\pm 2.04$
Stride 2	Exp	10.25	9.79	10.00	10.07	12.51	13.04
		$\pm 2.36$	$\pm 3.16$	$\pm 2.78$	$\pm 2.16$	$\pm 2.30$	$\pm 3.46$
	Con	12.21	15.18	9.98	10.30	14.50	12.90
		$\pm 7.59$	$\pm 6.69$	$\pm 2.46$	$\pm 1.74$	$\pm 4.75$	$\pm 2.48$
Stride 3	Exp	9.87	9.14	9.90	8.95	12.92	12.90
		$\pm 2.56$	$\pm 2.96$	$\pm 4.31$	$\pm 3.15$	$\pm 2.99$	$\pm 3.26$
	Con	11.76	14.28	10.21	11.63	12.81	11.93
		$\pm 3.99$	$\pm 9.26$	$\pm 3.08$	$\pm 3.50$	$\pm 4.50$	$\pm 4.10$

Note: Pre = pre-training; Post = post-training; Exp = experimental group; Con = control group.

There was a significant group  $\times$  testing occasion interaction for the RMSE values for the shoulder-hip CRP during stride 2 (Table 5.12). This interaction was caused by the experimental group becoming less variable in the coupling between the shoulder and hip joints from pre to post-training, while the control group became more variable. There were no significant main effects or interactions for the RMSE values of the other CRP measures.



**Table 5.12** Results of the ANOVA performed on the continuous relative phase variability for the shoulder-hip joint couplings during the first 3 strides of the 20 m sprint. Main effects and interactions are shown.

Stride	Main effects				Interaction	
	Testing occasion		Group		F ratio*	P value
	F ratio*	P value	F ratio*	P value		
Stride 1	1.68	0.215	1.12	0.306	0.96	0.343
Stride 2	0.46	0.507	0.86	0.368	5.05	0.040
Stride 3	0.31	0.587	3.59	0.078	1.01	0.331

Note: \* 1, 15 degrees of freedom.

## 5.2 Discussion

The principle aim of this investigation was to assess the effects of a resistance training intervention on co-ordination during the first 3 strides of a 20 m sprint. It was shown in Chapter 4 that the resistance training intervention increased muscular strength but did not decrease sprint time immediately after the training period. The present results demonstrated that the resistance training intervention caused an increase in the RoM about the shoulder and knee joints during the first 3 strides of the 20 m sprint. The increase in the RoM about the shoulder joint was caused mainly by an increase in the extension at around 50% of the stride cycles. At this point during each stride it is likely that the contralateral leg was approaching toe-off (assuming that the contralateral limbs are 180° out of phase during sprinting). Assuming that there was an increase in extension about the contralateral hip joint at toe-off (replicating the increase in extension about the hip at toe-off on the measured leg) then the increase in extension about the shoulder could represent a change in behaviour to compensate for the increased extension about the contralateral hip joint, preserving the co-ordination pattern between the non-homologous, contralateral limbs during the stride cycles.

An increase in extension about the hip and knee joints at toe-off during the first 3 strides of the sprint was also found in the present investigation. These increases may have allowed the mono-articular hip and knee extensors to perform more work prior to toe-off to contribute to the acceleration of the CoM. However, it has been reported that faster athletes have reduced hip and knee extension angles at toe-off compared to their slower counterparts (Mann & Herman, 1985; Murphy et al., 2003). A reduction in joint extension at toe-off increases stride frequency through a reduction in stance duration. In Chapter 4 it was reported that the experimental group decreased stride frequency following the resistance training intervention, although this change was likely to be due to the significant increases in the duration of the

flight periods with only slight increases in the stance durations during the first 3 strides. However, the increases in extension about the hip and knee joints could have contributed to the reduction in stride frequency. Therefore, despite the possible increases in work done by the mono-articular hip and knee extensors during the stance periods, the increases in extension about the hip and knee joints may have contributed to the increase in sprint time by reducing stride frequency because of slight increases in stance duration.

There was a change in the mean power spectrum for the angular displacement signal of the knee joint during stride 2, with a shift in power to the higher harmonics for the experimental group and a concomitant shift to the lower harmonics for the control group. The appearance of higher frequency components in the kinematic and kinetic signals associated with movements has been ascribed a functional role, reflecting the exploration of new co-ordination patterns by the motor system (Riccio, 1993). The exploratory behaviour is proposed to occur on spatial and temporal scales that are smaller than those characteristic of the performatory behaviour so as not to interfere with the movement task, and so higher frequency components of the movement signals emerge (Riccio, 1993). Therefore, a shift in power to the higher harmonics following a resistance training intervention could signify the exploration of the pattern of angular displacement about the knee joint to achieve the sprint task following an increase in muscular strength. This pattern may include an increase in the extension about the knee prior to toe-off to effectively accelerate the CoM horizontally, although the concomitant increases in stance duration, while only slight, would suggest that immediately following the training period the pattern was not optimal.

In the present investigation the comparison of individuals who responded very differently to the resistance training intervention in terms of the change in 10 m sprint times revealed different responses in the behaviour at certain joints, particularly the hip joint. Specifically, two individuals whose 10 m sprint time changed little ('maintenance responders') demonstrated large increases in extension about the hip, knee and ankle joints at toe-off during the first 3 strides. The changes about the hip and knee joints were associated with greater RoM about these joints during the stance periods, indicating an increase in the amount of work done by the hip and knee extensors during stance to accelerate the CoM horizontally. In contrast, two individuals whose 10 m sprint times were increased considerably following the resistance training intervention ('increase responders') demonstrated smaller increases in hip and knee extension at toe-off, but much greater increases in hip extension at touch-down. An increase in extension at touch-down may

reflect an earlier activation of the hip extensors during the stride cycle as an adaptation to the resistance training exercises. An earlier activation of the hip extensors would produce an extensor moment about the hip prior to touch-down. Such an adaptation contravenes the requirement of delaying the joint extensions until the CoM is beyond the GRF that would effectively accelerate the CoM horizontally (Jacobs & Van Ingen Schenau, 1992). The increase in joint extension during early stance would be expected to accelerate the CoM vertically as opposed to horizontally. In support of this suggestion, those participants identified as 'increase responders' demonstrated increases in the vertical impulse which were relatively greater than those demonstrated by the participants identified as 'maintenance responders'.

An increase in extension about the hip joint at touch-down would also reduce the effective mechanical advantage (EMA) at the joint. The EMA is defined as the ratio of the muscle mechanical advantage to the GRF mechanical advantage at a joint and represents the leverage with which a given muscle or group of muscles produce force against the ground during stance (Biewener, 1989). When sprinting from a standing start, the crouched posture produces a large hip extensor EMA generating large horizontal forces during stance (Card et al., 2001). In support of a possible reduction in the hip extensor EMA during stance, those participants identified as 'increase responders' who produced increases in extension about the hip at touch-down that were greater than those by the 'maintenance responders' also demonstrated the largest decreases in horizontal impulse during the first 3 strides of the 20 m sprint. The increased extension at touch-down could also reduce the range over which the hip joint was extended during the stance periods, and the 'increase responders' reduced the RoM about the hip joint during stance following the resistance training intervention. This would have limited the amount of work done by the mono-articular hip extensors during stance, possibly affecting the distal transfer of power from the hip joint to the ankle that is required to accelerate the CoM horizontally at toe-off during accelerative sprinting (Jacobs et al., 1996).

Despite the changes in behaviour at the individual joints, both the group and individual analyses revealed that the patterns of inter-joint co-ordination remained largely unchanged following the resistance training as evidenced by the relative phase measures. However, the maintenance of the pre-training inter-joint co-ordination patterns following an increase in muscular strength is likely to reflect the co-ordinative structures within the motor system. Specifically, co-ordinative structures are formed whereby groups of muscles are constrained

to act as single, functional units (Kugler et al., 1980). When constrained to function as a co-ordinative structure the individual muscles compensate to preserve the relationship of the collective unit in the face of changing system behaviour (Tuller et al., 1982). Generally, this behaviour was revealed in the present investigation where, for example, the changes at the hip joint (an increase in extension at toe-off) were compensated for by changes about the knee joint (a similar increase in extension at toe-off), maintaining the co-ordination pattern between the two joints during the stride cycle as assessed by RP measures. However, individual analyses revealed some instances where the changes in behaviour at one joint were not compensated for by changes at another joint, altering the relative phase between the joints following the resistance training. For example, in one participant (IF) the increases in plantar flexion about the ankle joint at touch-down were not compensated by concomitant changes at the knee joint, resulting in a change from positive to negative relative phase between the joints at this time. Changes in the relative phase measures for the shoulder-hip and hip-knee joint couplings were also found for this individual at touch-down during stride 1. Such changes, occurring late in the flight period, may have affected the propulsion during the stance period. Wood (1987) reported that better sprinters generate propulsive forces earlier during stance, and therefore co-ordination during the late stage of the flight period is important for effective force generation. It is worth noting that the individual who demonstrated changes in relative phase at touch-down (participant IF) substantially reduced the horizontal impulse during the first 3 strides of the sprint and increased 10 m sprint time by 9% following the resistance training intervention.

Changing the physical constraints of the motor system may require the formation of new co-ordinative structures which allow the individual to perform successful movements within the specific task demands once the appropriate level of constraint has been imposed. The qualitatively distinct co-ordination patterns of the developing child reported during locomotor tasks are typical of this scenario (Clark & Phillips, 1993; Robertson & Halverson, 1988). However, Handford et al. (1997) note that when co-ordination patterns for the particular task have been established and stable co-ordinative structures operate under the imposed constraints, then changes in the physical constraints of the motor system may only require a re-scaling of certain parameters in order to successfully meet the demands of the task. This appears to be the case in the present study where the displacement about certain joints was increased, while the established co-ordinative structures (inter-joint co-ordination patterns) were maintained during the sprinting task. However, under these conditions accelerative performance was not optimised. In a simulation study, Bobbert and Van Soest

(1994) reported that the performance of a vertical jump for maximum height was not optimised following an increase in the strength of the active muscles unless the activation pattern was concomitantly adapted to the new muscle properties. Although the participants identified as 'increase responders' appeared to alter the temporal behaviour of the joints, particularly the hip joint, it is possible that these changes were a result of maintaining the original muscle activation pattern with muscles that were now much stronger. For example, the increase in extension about the hip at touch-down exhibited by these participants may have been caused by the increased strength of the hip extensors (gluteus maximus, hamstrings) producing a greater extensor moment earlier during the stride cycle. Had the activation pattern been altered to allow a later activation of the hip extensors then these muscles could have contributed to the horizontal acceleration of the CoM at toe-off by increasing the extension once the CoM had moved anterior to the GRF during stance.

The resistance training intervention in the present investigation produced a reduction in the variability of the shoulder-hip CRP during stride 2 that was significantly different from the increase by the control group. Carroll et al. (2001a) reported an increase in the stability of co-ordination during a single-joint sensory-motor task following a period of resistance training. The authors also found that the muscles that were the target of the resistance training were recruited in a more consistent fashion following the training. This led the authors to speculate that the increase in the stability of the movement co-ordination resulted from a reduction in the interference between functionally proximal areas of the cerebral cortex. Specifically, it was suggested that fewer motor units were required to produce an equivalent movement given the increased force generated by the motor units following the resistance training. As such, the central drive necessary to perform the movement task was reduced and there was less interference within the cerebral cortex. A similar suggestion can be forwarded to explain the present findings, with the resistance training intervention increasing the force capabilities of the muscles about the hip and shoulder joints leading to a reduction in the central drive necessary to perform the sprinting movement. Why the reduction in variability only occurred for the shoulder-hip coupling is difficult to explain. A reduction in the variability associated with the co-ordination during the sprinting movement has implications for sprint tasks characterised by high spatio-temporal constraints, such as the long jump run-up (Glize & Laurent, 1997). If it could be shown that increasing muscular strength decreased the variability of the co-ordination during accelerative sprinting then this would provide coaches with a training method to improve performance in the jump not only

through increasing the force generated at take-off but also through enhancing the consistency of the run-up.

From the preceding discussion it is apparent that muscular strength can be considered as a potent physical constraint, specifying certain aspects during the co-ordination of the sprinting task. Following the resistance training intervention the angular displacement at the joints was increased during the first 3 strides of the 20 m sprint. However, it has been proposed that the non-linear mechanical properties of the active muscles provide the motor system with a mechanism for adapting to different internal and external demands (Chapman & Sanderson, 1990; Ettema, 2002; Gerritsen et al., 1998; Van Soest & Bobbert, 1993). As such, small increases in strength are likely to be accommodated into the existing co-ordination pattern due to the non-linear force-length-velocity relationships of the active muscles, with no need to change the co-ordination pattern for a given movement. Therefore, the magnitude of the gains in strength is likely to influence the magnitude of the changes in co-ordination following a resistance training intervention. To investigate this proposal an investigation was undertaken to assess the ability of the changes in the measures of strength to predict the changes in sprint performance and co-ordination reported in this thesis.



## 6. RESULTS AND DISCUSSION

**Can the changes in sprint time and the co-ordination of movement as a result of resistance training be predicted from the magnitude of the gains in strength?**

### 6.1 Results

Because the change in peak power output during the unloaded vertical jump condition for the experimental group was not significantly different from that for the control group, this measure of explosive strength was not included in the following analyses. Similarly, because of the large correlation between the change in peak power output during the vertical jumps with loads of 30% 1-RM and 60% 1-RM ( $r = 0.800$ ,  $P = 0.003$ ), only the change in peak power output with loads of 30% 1-RM is included as the measure of explosive strength in the following section.

#### 6.1.1 Changes in sprint time

Table 6.1 shows the partial correlations between the percentage change in the measures of maximum strength (1-RM squat) and explosive strength (peak power output 30% 1-RM) and the percentage change in the 10 m and 20 m sprint times. The correlation between the changes in maximum strength and the change in 20 m sprint time was positive, while the correlation between the change in explosive strength and the change in 20 m time was negative.

**Table 6.1** Partial correlations between the percentage change in measures of maximum and explosive strength and percentage change in 10 m and 20 m sprint time.

	Maximum strength change		Explosive strength change	
	$r$	$P$ value	$r$	$P$ value
Change 10 m time	0.406	0.119	-0.351	0.183
Change 20 m time	0.554	0.026	-0.595	0.015

Note:  $df = 14$ .  $r$  = partial correlation coefficient.

The results of the regression models to predict the change in sprint times from the change in the measures of maximum and explosive strength are shown in Table 6.2. For the prediction of the change in 10 m time, the change in maximum strength alone explained less than 6% of the variance and was not a significant predictor ( $F(1,15) = 0.89$ ,  $P = 0.361$ ). Combining the changes in maximum strength and explosive strength increased the amount of variance that could be explained in the change in 10 m times (17%), but the addition of the change in



explosive strength did not increase the predictive power of the model significantly ( $P > 0.05$ ). These findings are reflected in the model parameters (Table 6.3) which shows that the changes in maximum and explosive strength did not contribute significantly to the prediction of the change in 10 m time.

**Table 6.2** Regression statistics for the change in 10 m and 20 m sprint time predicted from changes in measures of maximum and explosive strength.

Outcome	Predictor	$R^2$	Adjusted $R^2$
Change in 10 m	Maximum strength†	0.056	-0.007
	Maximum and explosive strength	0.172	0.054
Change in 20 m	Explosive strength†	0.097	0.037
	Explosive and maximum strength	0.374	0.285

Note: † First variable entered into model.  $R^2$  = coefficient of determination.

**Table 6.3** Model parameters for the prediction of change in 10 m and 20 m sprint times from changes in measures of maximum and explosive strength.

Outcome	Model	Predictor	$\beta^*$	t	P value
Change in 10 m	1	Maximum strength	0.236	0.94	0.361
	2	Maximum strength	0.548	1.66	0.119
		Explosive strength	-0.462	-1.40	0.183
Change in 20 m	1	Explosive strength	-0.312	-1.27	0.223
	2	Explosive strength	-0.793	-2.77	0.015
		Maximum strength	0.713	2.49	0.026

Note: \* Standardised  $\beta$  coefficient.

The change in explosive strength alone was not a significant predictor of the change in 20 m time ( $F(1,15) = 1.62$ ,  $P = 0.223$ ). Combining the changes in explosive and maximum strength could explain 37% of the variance in the change in 20 m sprint times (Table 6.2). The addition of the change in maximum strength increased the predictive power of the model significantly ( $F(2,14) = 6.20$ ,  $P = 0.026$ ). The change in 20 m could be predicted from the change in the measures of explosive and maximum strength (Table 6.3), although they contributed in different ways, with an increase in explosive strength predicting a decrease in the 20m time and an increase in maximum strength predicting an increase in sprint time. The standardised  $\beta$  coefficients for the model combining the change in explosive and maximum strength to predict the change in 20 m sprint time (Table 6.3, model 2) indicated that a 5% increase in explosive strength could reduce 20 m sprint time by 2% (~ 2 ms). However, a 2%

(~ 2 ms) increase in 20 m sprint time was predicted from a 12% increase in normalised maximum strength.

6.12 Changes in joint ranges of motion

As the range of motion (RoM) about the knee joint was increased following the resistance training intervention (see Chapter 5), only the changes about this joint were analysed. Table 6.4 shows the partial correlations between the percentage change in the measures of maximum and explosive strength and the percentage change in the RoM about the knee joint during the first 3 strides of the 20 m sprint. The change in the measure of maximum strength was not significantly correlated with the change in the RoM about the knee joint during any of the first 3 strides of the 20 m sprint. However, there was a significant correlation between the change in explosive strength and the change in the RoM about the knee during stride 2.

**Table 6.4** Partial correlations between the percentage change in measures of maximum and explosive strength and percentage change in the range of motion about the knee joint during the first 3 strides of the 20 m sprint.

	Maximum strength change		Explosive strength change	
	<i>r</i>	<i>P</i> value	<i>r</i>	<i>P</i> value
RoM change stride 1	0.150	0.579	0.452	0.079
RoM change stride 2	0.029	0.916	0.520	0.039
RoM change stride 3	0.301	0.257	0.330	0.212

Note: df = 14. *r* = partial correlation coefficient; RoM = range of motion.

Because of the greater partial correlations, the changes in explosive strength were entered first into the regression models. The results of the regression models to predict the change in RoM about the knee joint are shown in Table 6.5. The change in explosive strength alone explained between 35% and 42% of the variance in the change in the RoM about the knee joint during the first 3 strides of the 20 m sprint. The change in the measure of explosive strength was a significant predictor of the knee RoM during stride 1 ( $F(1,15) = 9.97$ ,  $P = 0.007$ ), stride 2 ( $F(1,15) = 10.87$ ,  $P = 0.005$ ) and stride 3 ( $F(1,15) = 7.91$ ,  $P = 0.013$ ). Combining the changes in the measures of explosive and maximum strength increased the amount of variance explained in the change in knee RoM slightly, but the addition of the change in maximum strength did not increase the predictive power of the model significantly ( $P > 0.05$ ). These findings are reflected in the model's parameters (Table 6.6).

**Table 6.5** Regression statistics for the change in range of motion about the knee joint during the first 3 strides of the 20 m sprint predicted from changes in measures of maximum and explosive strength.

Outcome	Predictor	$R^2$	Adjusted $R^2$
RoM change	Explosive strength †	0.399	0.359
stride 1	Explosive and maximum strength	0.413	0.329
RoM change	Explosive strength †	0.420	0.381
stride 2	Explosive and maximum strength	0.421	0.338
RoM change	Explosive strength †	0.345	0.302
stride 3	Explosive and maximum strength	0.405	0.320

Note: † First variable entered into model.  $R^2$  = coefficient of determination; RoM = range of motion.

**Table 6.6** Model parameters for the prediction of change in range of motion about the knee joint during the first 3 strides of the 20 m sprint from changes in measures of maximum and explosive strength.

Outcome	Model	Predictor	$\beta^*$	t	P value
RoM change	1	Explosive strength	0.632	3.16	0.007
stride 1	2	Explosive strength	0.526	1.90	0.079
		Maximum strength	0.157	0.57	0.579
RoM change	1	Explosive strength	0.648	3.30	0.005
stride 2	2	Explosive strength	0.628	2.28	0.039
		Maximum strength	0.030	0.11	0.916
RoM change	1	Explosive strength	0.588	2.81	0.013
stride 3	2	Explosive strength	0.365	1.31	0.212
		Maximum strength	0.330	1.18	0.257

Note: \* Standardised  $\beta$  coefficient. RoM = range of motion.

The standardised  $\beta$  coefficients for the models containing the change in explosive strength to predict the change in the RoM about the knee joint indicated that a 5% increase in explosive strength predicted an increase in the RoM by 3% ( $\sim 3^\circ$ ) during the first stride of a 20 m sprint, while increases in the RoM about the knee of 5% ( $\sim 5^\circ$ ) were predicted during strides 2 and 3 following a 5% increase in explosive strength.

### 6.13 Changes in joint extension at toe-off

Increases in hip and knee extension at toe-off (TO) were found following the resistance training intervention (see Chapter 5). Therefore, only these changes were analysed. Table 6.7 shows the partial correlations between the percentage change in the measures of strength and

the percentage change in the TO angles at the hip and knee joints during the first 3 strides of the 20 m sprint.

**Table 6.7** Partial correlations between the percentage change in measures of maximum and explosive strength and percentage change in the toe-off angles at the hip and knee joints during the first 3 strides of the 20 m sprint.

Joint	Stride	Maximum strength change		Explosive strength change	
		<i>r</i>	<i>P</i> value	<i>r</i>	<i>P</i> value
Change hip TO	1	0.537	0.032	0.004	0.989
	2	0.367	0.162	0.264	0.323
	3	0.501	0.048	0.035	0.898
Change knee TO	1	0.305	0.251	0.118	0.664
	2	0.228	0.396	0.438	0.090
	3	0.233	0.385	0.153	0.571

Note: df = 14. *r* = partial correlation coefficient; TO = toe-off.

There were significant correlations between the change in maximum strength and the change in hip extension at TO during strides 1 and 3. As the correlations were greater between the change in maximum strength and most of the changes in the angles of extension at TO, this variable was entered first into the regression models. However, for the model to predict the change in knee extension at TO during stride 2 the change in the measure of explosive strength was entered first.

The results of the regression models to predict the change in the joint extensions at TO are shown in Table 6.8. For the prediction of the change in hip extension at TO, the change in maximum strength alone explained between 36% and 43% of the variance during the first 3 strides of the 20 m sprint. The change in the measure of maximum strength was a significant predictor of the change in hip extension at TO during stride 1 ( $F(1,15) = 11.23, P = 0.004$ ), stride 2 ( $F(1,15) = 8.60, P = 0.010$ ) and stride 3 ( $F(1,15) = 9.99, P = 0.006$ ). Combining the changes in maximum strength and explosive strength increased the amount of variance explained in the change in hip extension slightly, but the addition of the change in explosive strength did not increase the predictive power of the models significantly ( $P > 0.05$ ).

**Table 6.8** Regression statistics for the change in toe-off extension at the hip and knee joints during the first 3 strides of the 20 m sprint predicted from changes in measures of maximum and explosive strength.

Outcome	Predictor	$R^2$	Adjusted $R^2$
Change hip TO	Maximum strength †	0.428	0.390
angle stride 1	Maximum and explosive strength	0.428	0.346
Change hip TO	Maximum strength †	0.364	0.322
angle stride 2	Maximum and explosive strength	0.409	0.324
Change hip TO	Maximum strength †	0.400	0.360
angle stride 3	Maximum and explosive strength	0.400	0.315
Change knee TO	Maximum strength †	0.224	0.173
angle stride 1	Maximum and explosive strength	0.235	0.126
Change knee TO	Explosive strength †	0.420	0.381
angle stride 2	Explosive and maximum strength	0.450	0.371
Change knee TO	Maximum strength †	0.148	0.091
angle stride 3	Maximum and explosive strength	0.194	0.079

Note: † First variable entered into model.  $R^2$  = coefficient of determination; TO = toe-off.

The combination of the measures of strength could explain 24% and 19% of the variance in the change of knee extension at TO during strides 1 and 3, respectively, although the changes in the measures of strength were not significant predictors ( $P > 0.05$ ). However, the change in explosive strength could significantly explain 42% of the variance in knee extension at TO during stride 2 ( $F(1,15) = 10.85$ ,  $P = 0.005$ ). While combining the measures of maximum and explosive strength increased the amount of explained variance to 45%, the addition of maximum strength did not significantly increase the predictive power of the model ( $P > 0.05$ ).

Table 6.9 shows the model parameters for the contribution of changes in maximum and explosive strength to the prediction of hip and knee extension at TO during the first 3 strides of a 20 m sprint. The models containing the change in maximum strength to predict the change in hip extension at TO indicated that a 12% increase in maximum strength could increase the hip extension by 1% ( $\sim 2^\circ$ ) at TO during the first stride of the 20 m sprint. An increase in the hip extension at TO of 2% ( $\sim 3^\circ$ ) was predicted during strides 2 and 3, following a 12% increase in maximum strength. For the knee joint, a 5% increase in explosive strength was predicted to increase knee extension by 2% ( $\sim 3^\circ$ ) at TO during the second stride of a 20 m sprint.

**Table 6.9** Model parameters for the prediction of change in hip and knee extension at toe-off during the first 3 strides of the 20 m sprint from changes in measures of maximum and explosive strength.

Outcome	Model	Predictor	$\beta^*$	t	P value
Change hip TO angle stride 1	1	Maximum strength	0.654	3.35	0.004
	2	Maximum strength	0.652	2.38	0.032
		Explosive strength	0.004	0.01	0.989
Change hip TO angle stride 2	1	Maximum strength	0.604	2.93	0.010
	2	Maximum strength	0.411	1.48	0.162
		Explosive strength	0.285	1.02	0.323
Change hip TO angle stride 3	1	Maximum strength	0.632	3.16	0.006
	2	Maximum strength	0.608	2.17	0.048
		Explosive strength	0.036	0.13	0.898
Change knee TO angle stride 1	1	Maximum strength	0.474	2.08	0.055
	2	Maximum strength	0.379	1.20	0.251
		Explosive strength	0.141	0.44	0.664
Change knee TO angle stride 2	1	Explosive strength	0.648	3.29	0.005
	2	Explosive strength	0.489	1.82	0.090
		Maximum strength	0.235	0.88	0.396
Change knee TO angle stride 3	1	Maximum strength	0.385	1.61	0.127
	2	Maximum strength	0.188	0.58	0.571
		Explosive strength	0.291	0.90	0.385

Note: \* Standardised  $\beta$  coefficient. TO = toe-off.

## 6.2 Discussion

The principle aim of this investigation was to assess the ability of the magnitude of the changes in strength to predict the changes in sprint times and co-ordination during accelerative sprinting. The changes in maximum (1-RM squat) and explosive strength (peak power output during a vertical jump with 30% 1-RM) contributed significantly to predicting the change in 20 m sprint time, but not the change in 10 m sprint time. These differences are likely to reflect the different mechanical demands associated with the two sprint distances investigated, emphasising the need to consider sprint running as a multidimensional skill (Delecluse et al., 1995a). Specifically, neither measure of strength used in the present investigation incorporated the rotation-extension strategy that has been identified as a specific constraint associated with the stance periods of accelerative sprinting (Jacobs & Van Ingen Schenau, 1992). Therefore, due to the lack of mechanical specificity, neither strength measure could predict the change in 10 m sprint time. However, the second 10 m of the 20 m



sprint, when the participants were approaching maximum velocity, requires the application of greater vertical forces during stance to provide sufficient flight time to reposition the swinging leg (Weyand et al., 2000). This mechanical requirement is reflected in the squat and vertical jump exercises used to assess maximum and explosive strength, respectively.

The mathematical contribution of the two measures of strength to the prediction of the change in 20 m sprint time were similar in magnitude, yet both measures contributed to the prediction in different ways. An increase in explosive strength was predicted to cause a reduction in 20 m sprint time, while an increase in maximum strength was predicted to cause an increase in the sprint time. Gorostiaga et al. (2004) reported a significant relationship ( $r = 0.95$ ) between the increase in explosive strength (vertical jump height) and the increase in sprint velocity over 15 m following a combination of resistance and sprint training. This finding, and that of the present investigation, is likely to be influenced by the specificity of the muscle actions involved during the sprint in relation to the squat and vertical jump exercises. The squat requires large forces to be generated by the hip and knee extensor (gluteus maximus, vastii), particularly during the ascent phase (Caterisano et al. 2002). Although the vertical jump also requires large forces by these muscles (Bobbett & Van Ingen Schenau, 1988), the vertical jump requires the force to be generated over a much shorter duration than the squat. For example, an ascent phase of approximately 2 seconds has been reported for parallel squats with near-maximum loads (McLaughlin, Dillman & Lardner, 1978), while the propulsive phase of a vertical jump has been reported to be between 300 and 350 ms (Van Soest et al., 1993). The requirement for high forces to be generated during limited durations associated with the vertical jump reflect the requirements of sprinting at velocities approaching maximum where large vertical forces are required during reduced stance durations (Weyand et al., 2000). Therefore, the active muscles are required to generate large forces at high shortening velocities during vertical jumps and sprinting at maximum speed. These muscular qualities are highlighted in the strong relationships reported between the percentage of 'fast' muscle fibres and performance during vertical jumps and sprinting (Costill et al., 1976; Häkkinen, Alén & Komi, 1984; Mero et al., 1983; Viitasalo et al., 1981).

The finding that the increase in maximum strength predicted an increase in 20 m time is noteworthy. Although the squat exercise activates similar muscle groups that are required during the stance periods of sprinting, the squat exercise does not require the production of force to accelerate the CoM into a period of flight, with deceleration occurring towards the



end of the ascent phase of the squat (McLaughlin et al., 1977). Sprinting requires the acceleration of the CoM at toe-off with considerable transfer of power from the proximal hip joint to the distal ankle joint to achieve the necessary acceleration, even during the mid-acceleration phase of sprinting (Johnson & Buckley, 2001). While there is a similar proximal to distal transfer of power during the execution of vertical jumps (Jacobs et al., 1996), this requirement is unlikely to be necessary during the squat exercise where the vertical velocity of the barbell decreases to zero during the ascent (McLaughlin et al., 1977). It is possible that the squat exercise does not activate the particular pattern of muscle activations that optimises the distal transfer of power, but instead activates a pattern that actually interferes with this transfer. An interference of muscle activation patterns has been suggested to incur performance decrements following resistance training. For example, Carroll et al. (1998) reported that those participants who demonstrated the greatest increases in maximum strength in a trained movement (squat) failed to show an improvement in another maximum strength movement (knee extension). The authors proposed that the pattern of muscle activation that optimised the squat movement interfered with the performance of the knee extension movement. The negative transfer of muscle activation patterns from training movements to untrained tasks has been reviewed by Carroll et al. (2001b). These authors proposed that the enhancement of muscle activation patterns from trained movements could negatively influence the pattern of muscle recruitment during untrained strength tasks. It is possible that the adaptations to the squat exercise may have interfered with the muscle activation pattern that optimises the transfer of power distally to the ankle joint, although more complex methods of analysis would be required to confirm this speculation (e.g. EMG and kinetic data).

The present findings have significant implications for resistance training interventions to improve sprinting performance, suggesting that emphasis should be placed on developing explosive strength as opposed to maximum strength. However, due to the hierarchical nature of the relationship (e.g. Schmidtbleicher, 1992), the development of maximum strength is likely to be necessary before explosive strength can be developed fully. Therefore, the influence of the different expressions of strength on sprint performance reported in the present investigation may not be applicable following long-term resistance training.

From a dynamical systems perspective, muscular strength can be regarded as a constraint that shapes the co-ordination pattern during multi-joint movements. It was shown in Chapter 5 that the displacement about the hip and knee joints was increased during the first 3 strides

of the 20 m sprint following the resistance training intervention. Because of the non-linear mechanical properties of the active muscles, small changes in strength are likely to be accommodated into the original co-ordination pattern without the need to develop new patterns to satisfy the task demands. In this way the magnitude of the gain in strength is likely to influence the changes in co-ordination following a resistance training intervention. It was found in the present investigation that an increase in explosive strength contributed significantly to predicting the increase in the RoM about the knee joint during the first 3 strides and the angle of extension at this joint during the second stride of the 20 m sprint. The increase in extension about the knee joint at toe-off contributed to increases in the knee RoM during the stance periods (Chapter 5). The increase in the RoM during the stance periods would allow the mono-articular knee extensors to perform more work to accelerate to CoM. During a vertical jump it has been reported that the mono-articular knee extensors (vastii muscles) perform a greater amount of work during the last 90 ms of the propulsive phase than the mono-articular hip extensors (gluteus maximus), suggesting the importance of the knee extensors during a vertical jump (Jacobs et al., 1996). The knee extensors also perform a large amount of work prior to toe-off during accelerative sprinting (Jacobs et al., 1996), and so an increase in knee extension that contributes to the greater amount of work done during a vertical jump may have been transferred to the sprinting movement.

An increase in maximum strength was predicted to cause an increase in the extension about the hip joint at toe-off during the first 3 strides of the 20 m sprint. This relationship is likely to reflect the increase in strength of the hip extensors resulting from the resistance training intervention. The squat exercise, which was used to assess maximum strength, requires a large hip extensor moment during the ascent phase (Escamilla, Lander & Garhammer, 2000). An increase in the extensor moment would be expected from an increase in the strength of the hip extensor muscles (gluteus maximus, hamstrings) following a resistance training intervention. Such an adaptation would contribute to increasing hip extension at toe-off during accelerative sprinting. This change would increase the work done by the mono-articular hip extensors prior to toe-off.

This investigation has shown that an increase in muscular strength can contribute to the prediction of the change in 20 m sprint time, although the measures of maximum and explosive strength contributed to the prediction in different ways. These differences arise from the specific mechanical demands of the measures of strength. The changes in strength also contributed significantly to the changes in the hip and knee joint motions during the first

3 strides of the 20 m sprint. These findings emphasise the importance of muscular strength as a physical constraint that can influence movement, and ultimately performance, during accelerative sprinting in response to a resistance training intervention.

## 7. GENERAL DISCUSSION

### 7.1 Overview of findings

The results of this thesis demonstrate that an 8-week periodised resistance training intervention improved strength but did not improve accelerative sprint performance immediately following the training period. Analysis of the first 3 strides of the 20 m sprint showed that the decrement in 10 m sprint performance came from a reduction in stride frequency due to increases in the flight times associated with each stride. The resistance training exercises used in the training programme increased force in a vertical plane during stance but did not emphasise the rotation-extension strategy that has been identified as a constraint specific to the stance periods of accelerative sprinting. The rotation-extension strategy in which the direction of the GRF relative to the CoM changes during the stance periods maximises the horizontal velocity of the CoM at toe-off, while the vertical velocity of the CoM is minimised. This allows the production of long strides at high stride frequencies. It is likely that the strengthening of the extensor muscles of the lower limbs interfered with the usual co-ordination pattern that prevents the extension of the joints until the CoM is anterior to the GRF during the stance periods of the sprinting task. As such, the vertical impulse was increased during the first 3 strides of the sprint, increasing flight time and reducing stride frequency, while horizontal impulse was reduced, decreasing horizontal velocity.

The RoM about the shoulder and knee joints as well as hip and knee extension at toe-off were increased during the first 3 strides of the sprint following the resistance training intervention. Analysis of individual participants revealed that the change in the joint angular kinematics, particularly about the hip joint, often interfered with the effective horizontal acceleration of the CoM immediately after the training period. Some participants increased hip extension at touch-down so that the RoM about the hip during the stance periods was reduced. Given that horizontal forces were not increased, this would have reduced the amount of work done by the mono-articular hip extensors, limiting their contribution to the horizontal velocity of the CoM. It was suggested that the increased strength of the muscles in the absence of a concomitant change in the co-ordination pattern interfered with sprint performance.

Despite the changes in the behaviour at the joints, there were no substantial changes in the inter-joint co-ordination patterns as assessed by relative phase measures. The absence of any substantial changes in the inter-joint co-ordination is interesting in the light of the concept of

co-ordinative structures. It may be hypothesised that the co-ordinative structures encouraged the maintenance of the inter-joint co-ordination patterns while allowing adjustment of RoM and increased extension about the hip and knee joints at toe-off.

However, the changes in the patterns of co-ordination between the joints may be a gradual process. For example, Handford et al. (1997) suggested that a gradual change in the co-ordination pattern for a given movement may be expected if the existing co-ordination dynamics are similar to the task constraints. Given that all of the participants in the present investigations could perform the accelerative sprinting task initially, each having the appropriate co-ordination dynamics to satisfy the task demands, then an abrupt change in the co-ordination pattern is unlikely. Therefore, more substantive changes in co-ordination may have emerged over the period following the completion of the training period as the individuals were able to explore appropriate patterns given the change in the physical constraints of the motor system. In this respect, those participants who displayed the greatest increases in sprint time and the greatest changes in the joint angular kinematics immediately following the training period in the present investigation (the 'increase responders' in Chapter 5) may actually have improved accelerative sprinting performance over a longer period. The substantial changes in the joint angular kinematics recorded immediately following the training period for these participants may represent the motor system attempting to alter the co-ordination pattern to satisfy the task demands, commensurate with the change in the participant's physical constraints.

The multidimensional structure of sprinting was emphasised by the results of the regression analysis indicating that changes in the measures of strength contributed to the change in 20 m sprint time, but not 10 m sprint time. Similarly, the different mechanical requirements of the measures of maximum and explosive strength were highlighted with both measures contributing to the prediction of the change in 20 m sprint time in different ways, emphasising the specificity of these assessment measures.

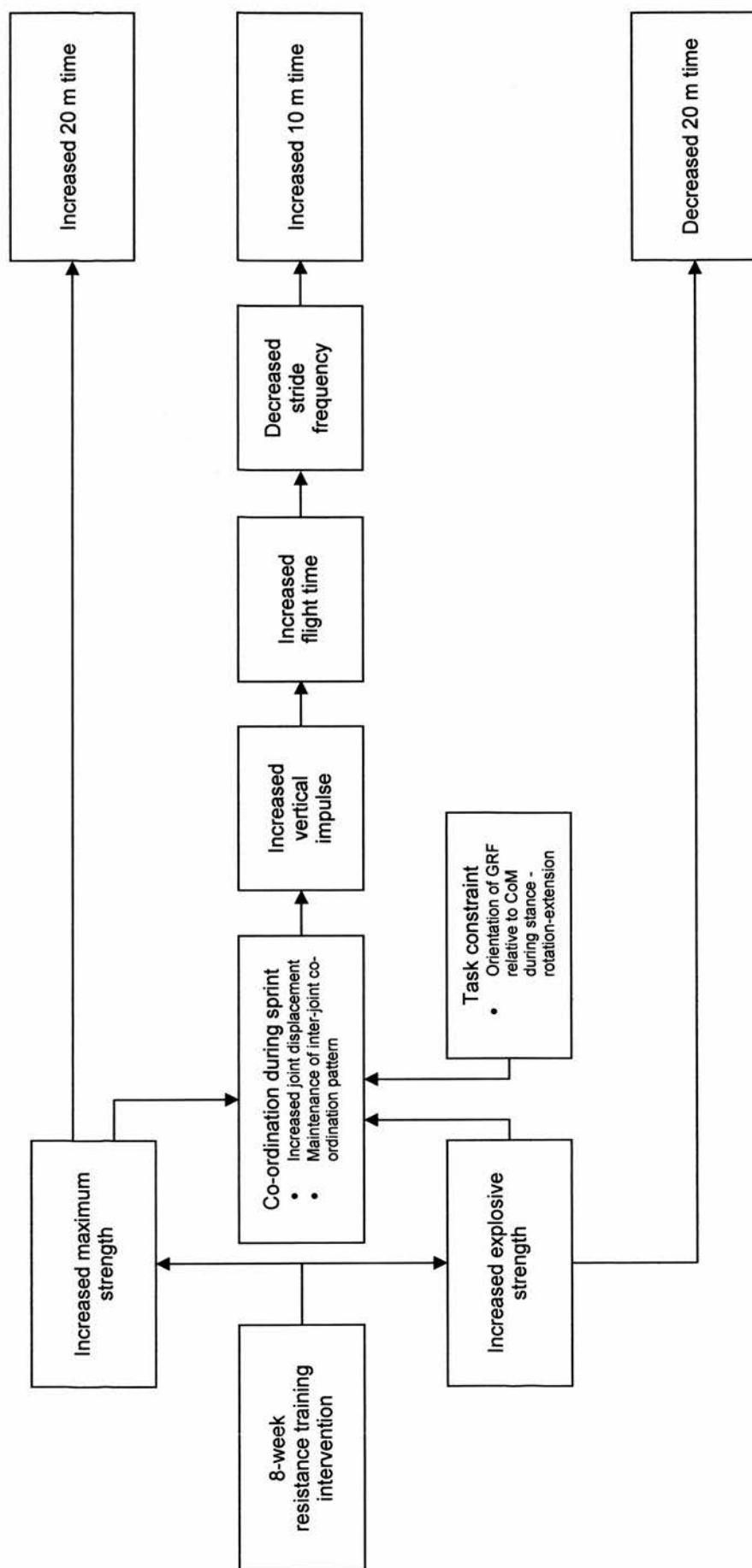
Changes in co-ordination were predicted following relatively large increases in strength. As the non-linear mechanical properties of the active muscles provide the motor system with a mechanism for adapting to different internal and external demands (Ettema, 2002; Gerritsen et al., 1998; Van Soest & Bobbert, 1993), small increases in strength are likely to be accommodated into the existing co-ordination pattern, without the need to change the activation patterns of the muscles. This may have been the case in the present investigation.

However, under these circumstances sprinting performance was not improved. Therefore, the original co-ordination pattern may represent that which ‘works’ rather than the ‘optimal’ co-ordination pattern for the movement (cf. Van Soest, Bobbert & Van Ingen Schenau, 1994), given the increases in muscular strength. It is likely that the maintenance of the original co-ordination pattern allowed the individuals to perform the movement in a way that was ‘familiar’ but did not optimise accelerative sprint performance. The proposed effects of an 8-week resistance training intervention on accelerative sprinting based upon the present investigations are summarised in Figure 7.1 overleaf.

## **7.2 Coaching implications**

Accelerative sprinting is an integral component of many sports, particularly field sports (e.g. soccer, rugby). Muscular strength has been identified as an important quality for successful performance during the acceleration phase of sprinting, and therefore resistance training has been proposed as an effective training method to improve accelerative sprinting (Dintiman et al., 1998; Donati, 1996; Sheppard, 2003; Young et al., 2001). In many sports, coaches have only short periods (4 – 8 weeks) in which to develop strength, due to competitions during the yearly training cycle. However, coaches should be aware of the potential adaptations to a short-term resistance training intervention, particularly those adaptations influencing the control and co-ordination of movement. Moreover, the identification of the constraints associated with the sprinting movement should expedite the transfer of strength gained from a resistance training intervention to sprinting performance. For example, the rotation-extension strategy proposed by Jacobs and Van Ingen Schenau (1992) is a specific constraint during accelerative sprinting that ensures a high horizontal velocity of the CoM at toe-off while the vertical velocity is low, allowing the production of long strides at high stride frequencies.

However, the resistance training exercises typically recommended in the sprint-training literature (e.g. back squat, Olympic lifts), do not emphasise this rotation-extension strategy. Therefore, coaches should consider the specificity of the resistance training exercises in relation to the athletic movement. The specificity of strength training exercises for sprinting has been assessed in terms of the times associated with the generation of force and the movement patterns (Mero & Komi, 1994). In relation to accelerative sprinting, Blazeovich et al. (1999) proposed that the forward hack squat exercise allowed athletes to train with a movement pattern similar to the stance periods of accelerative sprinting, reporting kinematic data (timing and displacement of joint angles) to substantiate the claim. However, while the



**Figure 7.1** A schematic illustration of the short-term effects of an 8-week resistance training intervention on accelerative sprint time. Note: GRF = ground reaction force; CoM = body centre of mass.



forward hack squat is specific to the stance periods during accelerative sprinting in terms of joint displacements and most likely replicates the direction of the application of force at the end of the stance periods, the exercise does not replicate the control of the direction of the GRF with respect to the CoM required during accelerative sprinting. In particular, the exercise is unlikely to involve the appropriate reciprocal activation of the biarticular hamstrings and rectus femoris muscles that controls the direction of the GRF during the stance periods. Therefore, the constraint associated with the stance period of accelerative sprinting that is crucial in the production of long strides and high stride frequencies remains untrained even in exercises that may have kinematic similarities to the sprinting movement. As the control of the GRF direction relies on the reciprocal action of the bi-articular hamstrings and rectus femoris muscles, then training the activation of these muscles in the specific movement is paramount if the strength gained from a resistance training intervention is to be transferred to accelerative sprinting.

Resisted sprinting, whereby the athlete sprints against a resistance (e.g. a weighted sled, a speed parachute), is a training exercise that would strengthen the appropriate muscles during the specific movement. Such methods have been proposed to develop the extensor muscles of the hip, knee and ankle joints (Delecluse, 1997), and would have the advantage of developing these muscles while allowing the athlete to train the specific rotation-extension strategy required during accelerative sprinting. However, despite their specificity, there have been no studies to date investigating the effects of chronic adaptations to resisted sprinting methods, although a number of cross-sectional studies have assessed the acute effects of resisted sprinting on the kinematics during sprinting (Letzelter, Sauerwein & Burger, 1995; Lockie, Murphy & Spinks, 2003). These authors reported a reduction in stride length and an increased forward lean of the trunk at touch-down, but the chronic adaptations to this method of training still require investigation.

Following a resistance training intervention there may be a period where the motor system searches for the optimal co-ordination pattern given the gains in muscular strength. For example, the increase in the higher frequency harmonics in the knee displacement signals reported in the present thesis may signify an exploratory period by the motor system. If this period indicates the readiness of the motor system to change behaviour then the coach can exploit this through the appropriate manipulation of the training environment to allow the athlete to explore possible co-ordination patterns to optimise the sprinting task. This could

explain why the combination of resistance training and sprint training have been effective in improving accelerative sprinting, even in untrained sprinters (e.g. Delecluse et al., 1995b).

The inclusion of specific drills that emphasise the development of the rotation-extension strategy would aid the exploratory process. However, drills such as the ‘acceleration ladder’ or the ‘agility ladder’, purported to improve accelerative sprinting by increasing stride frequency (Seagrave, 1996; Yap & Brown, 2000), may not be appropriate. These drills, which require the athlete to accelerate through a series of progressively spaced ‘rungs’ or small barriers on the floor, represent a manipulation of task constraints that force the athlete to adopt a co-ordination pattern that may not represent the appropriate solution to satisfy the task demands during a normal sprinting situation. However, research is required to investigate whether such drills would disrupt co-ordination during straight-line sprinting.

There was evidence of individual responses to the resistance training intervention in the present thesis, with the sprint performance of some participants changing little following the training while others slowed substantially. Therefore, athletes are unlikely to respond to a training intervention with similar changes in performance and coaches should attempt to account for these individual responses by implementing regular testing sessions to monitor the effectiveness of the training methods and then manipulate the training programmes of athletes on an individual basis.

The results of the present investigations suggest that the changes in both sprint performance and the changes in hip and knee joint motions during the sprinting movement are likely to be influenced by the magnitude of the gains in strength. The change in both maximum and explosive strength contributed significantly to the prediction of the change in 20 m sprint time but not 10 m time. However, the changes in the measures of strength contributed to the change in 20 m sprint time in different ways, with an increase in explosive strength predicting a decrease in sprint time and an increase in maximum strength predicting an increase in sprint time. These differences highlight the importance of viewing sprint running as a multidimensional skill. From this perspective, different training interventions could influence the performance during the disparate phases of a sprint in different ways and coaches should be aware of the likely impact of a particular training method. Similarly, coaches should consider the phase of sprinting that is important for the athlete’s performance and the associated constraints and use this to guide the selection of the appropriate training methods. The present findings also have implications for field-tests to monitor athletes, and

coaches should recognise that a single measure of sprint performance or strength may not provide the requisite information with which to make an informed judgement as to the benefits of a given training method.

Despite the use of short sprints replicating the distances typically covered in many field sports (e.g. Mayhew & Wenger, 1985; Meir, Arthur & Forrest, 1993), the present thesis was concerned only with straight-line sprinting. During most field-sports the athletes are required to sprint and change direction, and so agility becomes important. Straight-line sprinting speed and performance on a number of agility tests have been shown to be somewhat independent (Mayhew et al., 1989; Young et al., 1996). Young, McDowell and Scarlett (2002) reported little transfer from improvements in straight-line sprinting speed to 6 agility tests of differing complexity following a period of straight-line sprint training. It was found that the more complex the agility test (number of changes of direction) the less the transfer from the sprint training. It is likely that agility performance requires different strength qualities compared to straight-line accelerative sprinting (Young, James & Montgomery, 2002), and therefore the exercises used to improve straight-line sprinting may not be appropriate for agility.

Although agility performance can still be considered a ‘contact-control’ task like accelerative sprinting (Jacobs, Bobbert & Van Ingen Schenau, 1993) where the magnitude and direction of the GRF is constrained by the requirement to effectively accelerate the CoM, substantial differences exist in the forces required. For example, McClay et al. (1994) reported relatively small GRIs during the propulsion phase of cutting movements by professional basketball players. However, the GRIs associated with the braking phase were considerable, particularly in the medial direction. As such, a different pattern of co-ordination is likely to be required to satisfy the constraints of agility tasks compared to straight-line accelerative sprinting (cf. Neptune, Wright & Van den Bogert, 1999), and coaches should ensure that the resistance training exercises and drills used to improve agility reflect these differences. Similarly, in real-life sporting situations changing direction to pursue or evade an opponent or to intercept the ball is not a predictable task, and requires co-ordination of the movements within a visually structured environment (Lee & Young, 1986). Therefore, coaches should attempt to integrate the transfer of strength to agility movements that incorporate perceptual demands given the functional unity of the visual and motor systems within the organism-environment relationship (Lee, 1980; Turvey & Carello, 1986).

### **7.3 Limitations and future directions**

The co-ordination changes following an increase in muscular strength may be gradual, and therefore occur beyond the duration of the present investigation. An additional testing session to include assessment beyond the training period may have resulted in the identification of changes in the movement that optimised the sprint performance given the increases in strength.

The present study used a between-groups design to investigate the changes in sprint time and co-ordination. However, the examination of individual participants revealed substantial individual responses to the training. Therefore, a more detailed understanding of individual responses to strength training, including variability and stability of co-ordination patterns and sprint performance, could be gained from a research design emphasising a within-individual analysis.

While single-subject analysis has been promoted in biomechanical research (Bates, James & Dufek, 2004), it requires that the number of performance trials is increased to account for the heterogeneity in performance variability of the study participants and so increase the reliability of the measure and reduce the associated within-individual variation (Bates, Dufek & Davis, 1992). The number of trials required to provide a reliable and representative score for a given performance measure is likely to depend upon the measure itself. For example, Hunter et al. (2004b) predicted that a single trial was required to obtain a reliability of greater than 0.90 (using ICC) for step length during the acceleration phase of sprinting, while more than 5 trials were required to obtain a similar reliability score for the measure of relative vertical GRI. Salo, Grimshaw and Viitasalo (1997), studying the sprint hurdles, reported that 78 trials were required to obtain a reliable ( $ICC > 0.90$ ) measure of the loss of horizontal velocity of the CoM. However, the increase in the number of trials should be balanced against the nature of the test, as multiple trials of a maximal test (e.g. 20 m sprint) are likely to elicit considerable fatigue in the participants. This would introduce systematic error to the data, rendering it difficult to separate any changes in the movement resulting from the adaptations to a training intervention (e.g. resistance training) from the transient changes associated with muscular fatigue.

It was concluded in the present thesis that there were no improvements in sprint performance immediately following the resistance training intervention. However, this conclusion should be limited to the sample used in the present thesis. It is possible that improvements may have

been elicited if the investigation had been conducted using sprint or strength-trained participants. Moreover, although changes in the kinematic and kinetic stride variables and the co-ordination measures were found for the first 3 strides of the 20 m sprint, the analysis of the sprint times revealed possible changes occurring during the second 10 m of the 20 m sprint. For example, while sprint time over the initial 10 m was increased significantly following the resistance training regime, the time over the second 10 m was only increased slightly. It is possible that analyses of the stride cycles during the second 10 m would have yielded further information pertaining to the transfer of strength to sprinting performance. This is particularly important given the multidimensional structure of sprinting.

Although the kinematic and kinetic data recorded in the present investigations provided valuable information to explain the changes in sprinting performance following the resistance training intervention, a more thorough kinetic analysis of the movement could provide a more sensitive assessment of the adaptations. For example, while the kinematic descriptors of movement (e.g. joint angles) may remain stable across movement conditions, the kinetic aspects of the movement (e.g. joint moments and powers) can show marked variability (Winter, 1995). Future research should aim to include kinetic analyses, particularly given the importance of the proximal to distal transfer of power during accelerative sprinting and the changes in joint moments during the sprinting movement that were proposed in the present investigations. However, multiple trials are required to provide stable means in measures of joint moments and power outputs during explosive multi-joint movements (Rodano & Squadrone, 2002). It is also acknowledged that the proposed kinetic analyses would require more complex methods of data collection (e.g. a combination of EMG, force data and 3 dimensional analyses) and interpretation.

It is clear that further research is required into the effects of resistance training intervention on performance and co-ordination during sprinting. The contribution of the different expressions of strength (explosive versus maximum) to predicting the change in 20 m sprint time suggests that different resistance training regimes will confer different influences on performance during the distinct phases of sprinting. However, the inclusion of only one resistance training regime in the present thesis prevents further discussion of such possible influences. Including more training groups and manipulating the variables of exercise selection, loads, repetitions, sets and rest periods associated with the resistance training programmes to elicit changes in the different expressions of strength would further the knowledge of the effects of resistance training interventions on sprinting performance.



In the present investigation, explosive strength under the unloaded condition was not improved. This is likely to have been due to the inappropriate manipulation of exercise loads during the training programme and so a different training programme design may have provided a stimulus that improved explosive strength under unloaded as well as loaded conditions. For example, the use of lower resistances in the present training programme, particularly during the 'light' training sessions, is likely to have resulted in a gain in explosive strength under unloaded conditions. Such a change to the resistance training programme may have affected the sprint performance differently. For example, McBride et al. (2002) reported a significant improvement in 10 m sprint performance following a resistance training intervention using relatively light jump squats (30% 1-RM).

In relation to the resistance training intervention used in the present investigation, it is clear that the adaptations to the training stimulus were short-term given the duration of the study. Therefore, the present thesis provides little information pertaining to the effects of long-term resistance training on accelerative sprint performance. It is likely that the increases in strength elicited were the result of neural adaptations to the training stimulus, although a 4-week familiarisation period was included in an attempt to overcome many of these adaptations. However, the results of the anthropometric data (body mass, percent body fat) would suggest that there was unlikely to have been any substantial hypertrophy, although such crude methods do not allow the identification of possible 'remodelling' occurring within the muscle fibres (e.g. MHC transformations). Therefore, including EMG data and muscle biopsies in future research would provide further information about the specific adaptations to the resistance training stimulus and also relate the co-ordination changes to specific neuromuscular constraints within the motor system.

The short training period studied in the present thesis provides little information about the responses to long-term resistance training programmes typically experienced by athletes. In long-term periodised resistance training programmes, general or non-specific training is required to provide a base from which to attain higher levels of the most important physiological qualities and for injury prevention (Stone et al., 2000). Therefore, across a multi-year period, strength training should progress from general strength stimulus to sport-specific exercises as the competitive peak approaches (Baker, 2001; Stone et al., 2000). Although the resistance training exercises used in the present thesis may not have been specific to accelerative sprinting, they undoubtedly provided the participants with a 'general' base of strength. However, while performance improvements may be observed in the early

stages of training, with increased adaptation a general strength stimulus will not provide an adequate overload (Baker, 2001), and therefore more research is required with longer resistance training programmes that develop strength through specific exercises.

#### **7.4 Conclusion**

The results of the present thesis demonstrate that an 8-week periodised resistance training intervention increased muscular strength but did not improve accelerative sprint performance immediately following the training period. The angular displacement about the hip and knee joints was increased during the first 3 strides of the 20 m sprint. However, the original inter-joint co-ordination pattern was maintained. Maintaining the original inter-joint co-ordination pattern appeared inappropriate given the increase in the strength of the extensor muscles. It is likely that the increased strength, while increasing vertical impulse, reduced horizontal impulse due to a less than optimal implementation of the rotation-extension strategy.

The changes in measures of maximum and explosive strength could significantly predict the change in 20 m sprint time. Moreover, an increase in maximum strength was predicted to cause an increase in 20 m sprint time, whereas an increase in explosive strength was predicted to cause a decrease in sprint time. The magnitude of the gains in strength also contributed to the change in angular displacement about the hip and knee joints, highlighting muscular strength as a physical characteristic that constrains the behaviour of certain joints during the accelerative sprinting movement. The present findings highlight the complex interaction that exists between a resistance training regime, the individual and the sprint task. Improvements in accelerative sprinting performance cannot be expected until an appropriate co-ordination pattern is adopted that is commensurate with the changed constraints of the motor system.



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## APPENDICES

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## **APPENDIX A1.1 – INFORMED CONSENT FOR A STUDY ON THE EFFECTS OF RESISTANCE TRAINING ON STRENGTH, POWER AND SPRINT PERFORMANCE.**



Different modes of resistance training are proposed to improve various measures of strength and power and improve athletic qualities such as sprint running. The purpose of the proposed study is to assess the effect of a periodised resistance training programme on maximum strength, power and accelerative sprint performance. All training and testing will be performed within the St. Leonard's building.

### **Training programme.**

The training programme will last for 14 weeks. There will be one resistance training group and one non-training control group. The resistance training group will follow an 8-week periodised weight training programme with 3 sessions each week designed to improve strength and power. The control group will not train. Before the training programme begins there will be a 4-week familiarisation period provided for the training and testing exercises. For the duration of the study participants are requested to refrain from resistance or sprint training other than that provided in the study.

### **Testing sessions.**

There will be 2 testing weeks during the study (pre- and post-training sessions). Each testing week will incorporate three 40 minute sessions separated by one day. The following tests will be performed: 1) 1-RM testing (Monday), 2) Anthropometric tests (Tuesday), 3) 20 m sprint (Thursday), 4) Loaded vertical jumps (Friday).

- 1) 1-RM testing – To assess maximal strength a 1 repetition maximum (1-RM) test will be performed on the bench-press and the parallel squat. These tests will be performed using free weights.
- 2) Anthropometric tests – Measures of height, body mass and percent body fat will be taken.

- 3) 20 m sprint – Sprinting speed will be assessed with timing gates over a straight-line 20 m distance. Within the 20 m an intermediary distance of 10 m will also be measured. The sprints will be performed from a standing start.
- 4) Loaded vertical jumps – To assess power under different movement velocities vertical jumps will be performed under different load conditions. Free weights will be used to supply the extra load. The loads used will include 0 kg (unloaded), 30% 1-RM squat and 60% 1-RM squat. The tests will measure the force-time characteristics under the different loading conditions.

Although you will be undergoing strenuous exercise, there is very little risk if you are a normal healthy individual. Individual information obtained from this study will remain confidential. Non-identifiable data will be used for scientific presentations and publications. You may withdraw from the study at any time. If you have any questions please ask Gavin Moir before signing this consent form.

If you have any additional questions during or after the study, Gavin can be contacted at:

[gavin\\_moir@education.ed.ac.uk](mailto:gavin_moir@education.ed.ac.uk) Tel: 0131 6509788

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED AND YOU HAVE DECIDED TO PARTICIPATE IN THE STUDY.

I have read and understood the above explanation of the purpose and procedures for this study and agree to participate. I also understand that I am free to withdraw my consent at any time.

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Witness

\_\_\_\_\_  
Date

## **APPENDIX A1.2 – RESISTANCE TRAINING PROGRAMME**

### **SELECTION OF EXERCISES**

Major and assistance exercises were included in the training programme (Tables 1 & 2). Major exercises are multi-joint movements involving the major muscle groups, while assistance exercises are single-joint movements that train smaller muscle groups (Kraemer, 2002). The major exercises involved multi-joint movements comprising of squatting, pressing and pulling movements, while the assistance exercises were employed to emphasise the musculature of the shoulder girdle and the abdominal/lumber regions. The exercises used in the training programme are typical of those recommended in sprint-training texts to improve strength (e.g. Dintiman, Ward & Tellez, 1998; Sheppard, 2003; Young et al., 2001).

#### **Parallel squat**

The parallel squat is a closed kinetic chain movement that has been proposed as specific to the sprinting movement (Donati, 1996). The parallel squat involves the participant descending until the top of the thighs (line from the inguinal fold to the top of the patella) are parallel to the ground. The squat has been shown to activate the quadriceps (particularly vastus lateralis [VL] and vastus medialis [VM]), hamstrings and gluteals, with only moderate activity of the gastrocnemius (Escamilla, Lander & Garhammer, 2000). The activity of the quadriceps (VL, VM and rectus femoris) and gluteus maximus increases with knee flexion up to 90° during the descent (Caterisano et al., 2002; Escamilla et al., 1998).

#### **Power clean**

The power clean is a whole body exercise involving most of the lower limb musculature and the trapezius and the deltoid muscles (Graham, 2000). The power clean is recommended as a resistance training exercise in the development of muscular power because of the high power outputs that are developed during the movement, particularly during the second pull phase (Escamilla et al., 2000; Haydock, 2001). The power clean differs from the squat clean in that the bar is caught with less knee flexion in the power clean. Stone (1993) proposed that the movement during the second pull of the clean imitates that used in many sporting movements in terms of the joint angles and velocities.

#### **Stiff-legged deadlift**

The deadlift involves the musculature of the lower limbs (particularly that crossing the hip and knee joints) and the lower back (Escamilla et al., 2000). The stiff-legged deadlift (SLDL) differs from the conventional deadlift in that the knee flexion remains constant



throughout the SLDL movement and it involves an initial descent with the load. The SLDL is often used as an adjunct in the development of the power clean (Frounfelter, 2000).

**Table 1** Outline of the exercises used in the strength endurance microcycle of the resistance training programme.

Exercise	Day	Sets	Repetitions	Target RM	
Parallel squats	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Bench-press	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Push-press	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Flys	M & Fr	3	12	12-RM (M)	12-RM – 20% (Fr)
Sit-ups	M & Fr	3	15 - 25	–	–
Power cleans	We	3	12	12-RM – 10% (We)	
SLDL	We	3	12	12-RM – 10% (We)	
CGSS	We	3	12	12-RM – 10% (We)	
THE	We	3	15 - 25	–	

Note: M = Monday (heavy); We = Wednesday (moderate); Fr = Friday (light); RM = repetition maximum; SLDL = stiff-legged deadlift; CGSS = clean grip shoulder shrugs; THE = trunk hyperextensions.

**Table 2** Outline of the exercises used in the maximum strength and power microcycle of the resistance training programme.

Exercise	Day	Sets	Repetitions	Target RM	
Parallel squats	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
Bench-press	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
Push-press	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
Flys	M & Fr	3	5	5-RM (M)	5-RM – 20% (Fr)
SU (5 – 10 kg)	M & Fr	3	10 - 15	–	–
Power cleans	We	3	5	5-RM – 10% (We)	
SLDL	We	3	5	5-RM – 10% (We)	
CGSS	We	3	5	5-RM – 10% (We)	
THE (5 – 10 kg)	We	3	10 - 15	–	

Note: M = Monday (heavy); We = Wednesday (moderate); Fr = Friday (light); RM = repetition maximum; SU = sit-ups; SLDL = stiff-legged deadlift; CGSS = clean grip shoulder shrugs; THE = trunk hyperextensions.

### Push-press

The push-press is a multi-joint exercise that involves the majority of the lower limb and the deltoid muscles (Earle & Baechle, 2000). The rapid hip and knee extension to accelerate the load emphasises the development of power in the knee and hip extensors.

### **Bench-press**

The bench-press is a multi-joint exercise that it used to develop strength in the chest and shoulder-girdle. The major muscles activated during the movement include pectoralis major, deltoids, triceps brachii and the biceps brachii (Newton et al., 1996).

### **Clean-grip shoulder shrugs**

Clean-grip shrugs are used as an adjunct in the development of the power clean. The exercise primarily involves the trapezius and deltoid muscles.

### **Bent-knee sit-ups**

Sit-ups were included as an assistance exercise for the abdominal muscles. Sit-ups have been shown to recruit the abdominal muscle group and the hip flexors (Ricci, Marchetti & Figura, 1981), although less hip flexor involvement occurs when the knees are flexed during the movement, as in the present protocol.

### **Trunk hyperextensions**

The trunk hyperextension exercise is an assistance exercise used to strengthen the musculature of the lower back.

### **Flat dumbbell flys**

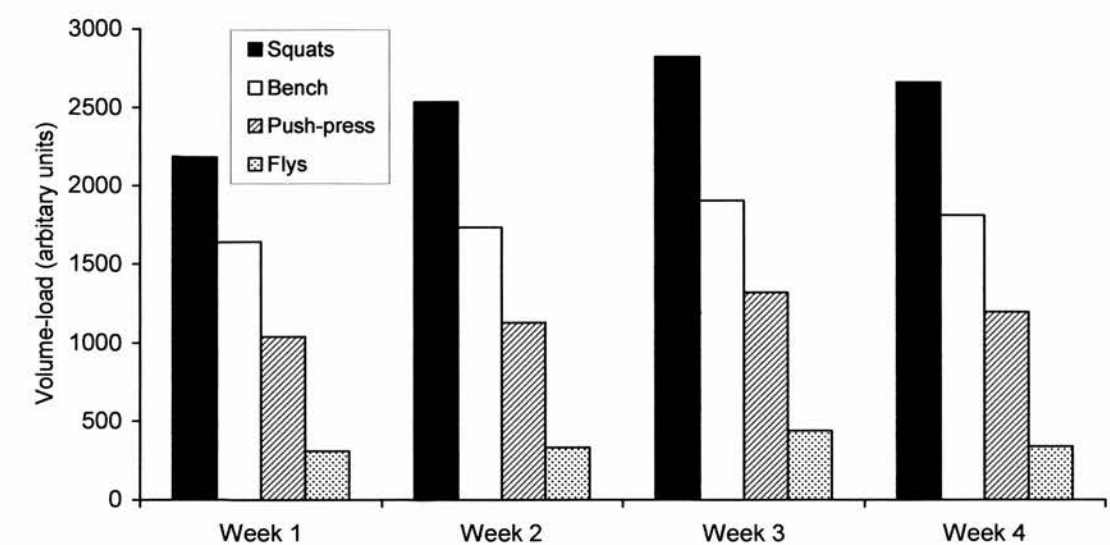
Flat dumbbell flys were included as an assistance exercise in the development of the musculature of the chest. Pectoralis major is the main muscle group recruited during this exercise (Earle & Baechle, 2000).

During each training session the large muscle group multi-joint exercises were performed before the smaller muscle group, single joint exercises to prevent excessive fatigue during the former (Kraemer, 2002). Teaching points for each of the exercises appear at the end of this section. The teaching points were taken from a number of references (Earle & Baechle, 2000; Frounfelter, 2000; Graham, 2001; Graham, 2000; Pierce, 1999).

## **PROGRAMME DESIGN**

The programme consisted of two microcycles of 4-weeks in length, the first emphasising strength endurance while the second emphasised the development of maximum strength and power. Microcycle one comprised 4-weeks of 3 x 12 repetitions at 12-repetition maximum (RM) while microcycle two comprised 4-weeks of 3 x 5 repetitions at 5-RM. During

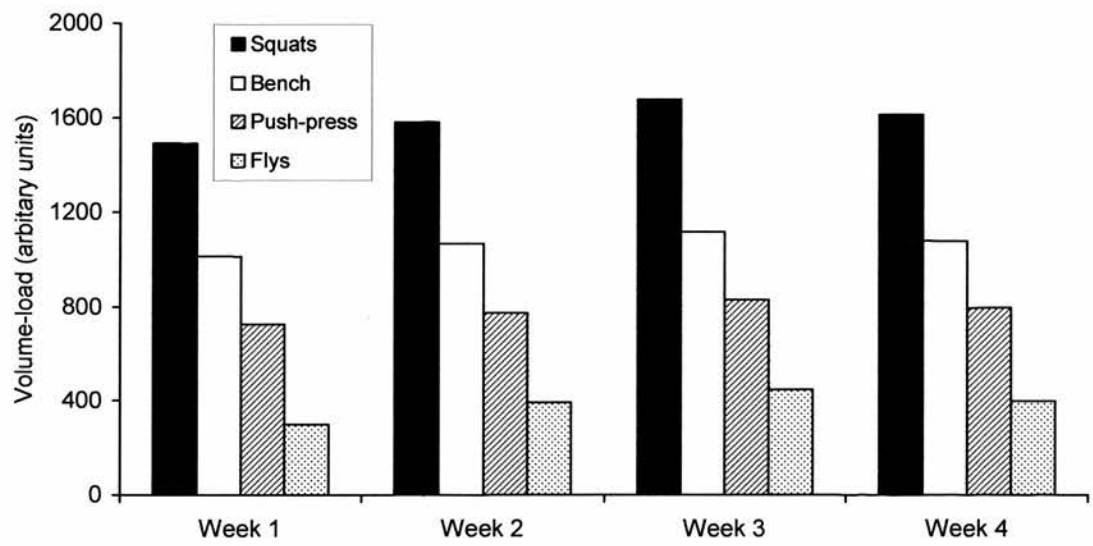
microcycle one 2-minutes rest was permitted between exercise sets, while 3-minutes were permitted during microcycle two (Kraemer, 2002). Within each microcycle the exercise loads were increased during the first 3-weeks by between 5% and 10% to ensure a training response. During the fourth week there was a reduction in load (Figures 1 & 2). This method of varying the load reduces the risk of overtraining (Stone et al., 2000). Three training sessions were performed each week, allowing one rest day between sessions, which was deemed appropriate (Kraemer, 2002).



**Figure 1** The volume-load for each of the 4 exercises during the heavy days of the strength endurance phase of the resistance training programme.

The training loads during each microcycle were set using a target RM procedure (Kraemer, 2002). The RM loads were determined during a 4-week familiarisation period conducted prior to the training and also through the use of a prediction chart (Baechle, Earle & Wathen, 2000). The training frequency was 3 times per week, incorporating heavy (Monday), moderate (Wednesday) and light (Friday) training days to reduce the risk of overtraining (Stone et al., 2000). The combination of heavy and light sessions has been recommended to provide a greater stimulus for the neuromuscular system to adapt, allowing a greater transfer to athletic movements that rely on power and speed (Baker, 1996; Cronin, McNair & Marshall, 2002; Newton & Kraemer, 1994; Stone, 1993). Variations in the loads were achieved by reducing the target RM by 10% on moderate days and 20% on light days (Tables 1 & 2). Exercise variation was also used to reduce the risk of overtraining. Different exercises were performed on the medium days compared to the heavy and light days (Tables

1 & 2). The manipulation of the training variables of volume, intensity and exercise selection during a resistance training programme has been hypothesised to reduce overtraining and increase performance (Fleck, 2002; Kraemer, 1997; Stone, 1990; Willoughby, 1991).



**Figure 2** The volume-load for each of the 4 exercises during the heavy days of the maximum strength and power phase of the resistance training programme.

As well as determining the RM loads for the exercises, the 4-week familiarisation period was incorporated to counter the possibility of learning mechanisms being responsible for the gains in strength (Jones & Rutherford, 1987). The familiarisation period was conducted prior to the assignment of participants into the experimental and control groups. During this period the participants performed all of the training and testing exercises.

Each training session was supervised by an instructor to ensure that the participants adhered to the programme and that the appropriate safety factors were used (e.g. spotting of the participants). Log books were kept by each participant and these were reviewed after each session by the instructor. Volume (number of repetitions) and intensity (load lifted) gained from the log books was used to calculate volume-load for each exercise during the training sessions for all participants in order to estimate the work performed during each session (Fry, Häkkinen & Kraemer, 2002; Stone et al., 2000). Examples of the volume-loads are shown in Figures 1 and 2. Prior to each training session, a standardised warm-up was performed by each participant. Briefly, this warm-up consisted of a period of 5-minutes of jogging, followed by a series of dynamic stretches (Appendix A1.3).

## TEACHING INSTRUCTIONS FOR THE EXERCISES

### **Parallel back squat**

In Power-rack using Olympic bar and weights.

#### *Starting position*

- Bar placed above posterior deltoids, with the hands slightly wider than shoulder width holding the bar.
- Scapulae pulled toward one another, chest held up and out, head tilted slightly up.
- Once bar is lifted, take one step back and position feet slightly wider than shoulder-width apart, evenly and pointing slightly outwards.

#### *Descent*

- Allow hips and knees to flex while maintaining flat, or slightly lordotic back position, and elbows kept high.
- Continue to flex hips and knees while keeping the heels on the floor and maintaining torso position (flat or slightly lordotic back).
- Descend until the thighs are parallel with the ground. Do not relax the torso when the bottom of the movement is reached.

#### *Ascent*

- Extend hips and knees while maintaining the position of the torso.
- Do not flex the torso or round the back.
- Continue to extend the hips and knees while keeping the heels on the ground, the elbows held high and the chest held up and out.

Repeat until set completed. Once completed, step forward towards the rack and squat down until the bar is back on the rests.

## **Power clean**

On lifting platform using Olympic bar and weights.

### *Starting position*

- Approach the bar with the hands slightly wider than shoulder width apart and the feet placed under bar, pointing slightly outward. The shins should be approximately 2-4 cm from the bar.
- The bar is grasped with a closed grip. The hips and knees are flexed while the elbows are maintained in a fully extended position as the bar is grasped.
- The back should be held flat or slightly lordotic with the shoulders held slightly over the bar. The head should be held slightly up.

### *Ascent*

- The bar is lifted from the floor by extending the hips and knees, while the elbows remain extended and the back retains the flat or lordotic position. The hips should not rise above the shoulders.
- As the bar is raised it should be kept as close as possible to the shins.
- As the bar is raised just above the knees, the hips are thrust forward, while the knees are re-flexed slightly. This action moves the thighs under the bar. The elbows remain fully extended.
- The hips and knees are quickly extended, while the ankles are plantar-flexed.
- The bar remains close to the thighs and the elbows remain fully extended through-out
- Once the hips and knees are fully extended, the shoulders should be shrugged to their highest elevation.
- As the bar continues to rise descend under the bar by flexing the knees and rotate the elbows so that the bar is caught on the shoulders with the elbows slightly elevated.
- Rise to a standing position.

### *Descent*

- Extend the elbows to lower the bar to the thighs, ensuring that it is kept close to the body throughout.
- The bar should be lowered to the floor by flexing the knees and hips while maintaining a flat or slightly lordotic back position and fully extended elbows.

Repeat until the set is completed.

### **Stiff-legged deadlift**

On lifting platform using Olympic bar and weights. Bar starts on blocks.

#### *Starting position*

- Grasp the bar slightly wider than shoulder width, with a closed, alternated grip.
- Take the bar from the blocks and take a step backwards.
- The feet should be slightly wider than hip-width and pointing forward. The knees slightly bent.
- The bar should be touching the front of the thighs, the elbows fully extended.

#### *Descent*

- Allow the torso to flex forward slowly so that the bar is lowered to the floor.
- Keep the knees slightly flexed and the back flat.
- Lower the bar to a point before the back begins to round or the knees begin to extend (this position will occur when the bar is approximately at the height of the knees).

#### *Ascent*

- Keeping the knees slightly flexed and the back flat, raise the bar by extending the hips and torso.
- Do not jerk the torso or flex the elbows to aid the movement.

Repeat until the set is completed. Step forward and place the bar back on the blocks after each set.

### **Push-press**

In Power-rack using Olympic bar and weights.

#### *Starting position*

- Grip the bar slightly wider than shoulder width, and approach the bar placing it on top of the anterior deltoids and clavicles.
- Lift the bar from the rack by extending the hips and knees, and take a step backwards.

#### *Ascent of bar*

- With the bar held on the front of the chest, perform a slight dip by flexing the hips and knees.
- Forcefully and quickly extend the knees, hips and then elbows and press the bar overhead.



- Once the bar is overhead, ensure that the elbows are fully extended, the head is in a neutral position, the torso is erect and tight, the feet are flat on the ground, and the bar is slightly behind the head.

#### *Descent of bar*

- Lower the bar back to the chest in a controlled manner; simultaneously flex the hips and knees slightly to cushion the bar.

Repeat until set completed. Once completed, step forward toward the rack and squat down until the bar is back on the rests.

### **Flat bench-press**

On a flat bench using Olympic bar and weights.

#### *Starting position*

- Assume a supine position on the bench with the feet place on the ground. The eyes should be below the edge of the bar supports.
- Grasp the bar with a closed, pronated grip slightly wider than shoulder width.
- The spotter aids the participant in moving the bar from the supports. The bar should be held over the chest with the elbows fully extended.

#### *Descent*

- The bar is lowered so it contacts the chest at the level of the nipples.
- The wrists are kept rigid and directly above the elbows.
- The feet remain in contact with the ground.

#### *Ascent*

- Maintaining rigid wrists and with the feet in contact with the ground the bar is raised by extending the elbows.
- The back should remain in contact with the bench through out the ascent.

Repeat until the set is completed. Once the set has been completed, the spotter will aid the participant in racking the bar. The participant must retain a grip on the bar until the bar has been racked.

### **Clean-grip shoulder-shrugs**

On lifting platform using Olympic bar and weights. Bar starts on blocks.

#### *Starting position*

- Grasp the bar slightly wider than shoulder width, with a closed grip.
- Take the bar from the blocks and take a step backwards.
- The feet should be slightly wider than hip-width and pointing forward. The knees slightly bent.
- The bar should be touching the front of the thighs, the elbows fully extended.
- The back should be held flat with the head held slightly up.

#### *Ascent*

- The bar remains close to the thighs and the elbows remain fully extended through-out the movement.
- The shoulders should be shrugged to their highest elevation. The bar should then be lowered to the thighs by relaxing the shoulders. The movement should be performed quickly.

Repeat until the set is completed. Step forward and place the bar back on the blocks after each

### **Bent-knee sit-ups**

On floor mat.

#### *Starting position*

- Assume supine position on floor, with the knees flexed and held close to the buttocks.
- Fold arms across the chest.

#### *Ascent*

- Keeping the arms across the chest and the feet and buttocks on the floor, flex the torso towards the thighs until the upper torso is off the mat.

#### *Descent*

- Allow the upper torso to descend towards the floor while keeping the feet and buttocks on the floor.

Repeat until the set is completed.

## **Trunk hyperextension**

On flat bench.

### *Starting position*

- Assume prone position on flat bench, with torso beyond the end of the bench. The feet should be held by a partner.
- Fold arms across the chest.

### *Descent*

- Keeping the arms across the chest, allow the torso to flex in a controlled manner moving the head towards the floor.

### *Ascent*

- The chest should be raised upward by contracting the muscles in the back, buttocks and hamstrings, while keeping the arms across the chest.
- Continue raising the chest until the torso becomes slightly hyperextended.

Repeat until the set is completed.

## **Flat dumbbell fly**

On a flat bench using dumbbells.

### *Starting position*

- Assuming a supine position on the bench with the feet on the floor, the dumbbells are handed to the participant by the spotter. The participant grasps them with a closed grip.
- Both dumbbells are pressed in unison above the chest with the elbows fully extended. The dumbbells are rotated to a neutral grip.
- The elbows are then slightly flexed and pointed outwards.

### *Descent of dumbbells*

- The dumbbells are lowered in a wide arc until they are level with the shoulders.
- The dumbbell bars are held parallel to one another during the descent.
- The wrists are held rigid and the elbows are held in a slightly flexed position throughout.
- The feet remain on the floor.

### *Ascent of dumbbells*

- The dumbbells are pulled towards each other in a wide arc to the starting position.

- The feet remain in contact with the floor and the elbows are held in a slightly flexed position.

Repeat until the set is completed. Once completed, the spotter aids the participant in returning the dumbbells to the floor.

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## APPENDIX A1.3 – WARM-UP PROTOCOLS

The warm-up protocols were developed from Blazeovich (2001), Hedrick (2000), Holcomb (2000) and Warden (1986). The dynamic stretches were performed before all training sessions and prior to the static jump tests. Prior to the 20 m sprint trials dynamic and static stretches as well as the sprint drills were performed.

### Dynamic Stretching

1. Start – 5-minutes of jogging.
2. **Body squats** – Arms across chest, slowly descend until the tops of the thighs are parallel to the ground. 10-repetitions.
3. **Lunge walk** – Arms across chest, step forward and slowly drop into a lunge position. Pause at the bottom of the move and then repeat with the opposite leg. Walk forward for a distance of approximately 10 m.
4. **Walking knee tuck** – Step forward with the left leg and using the hands to assist, squeeze the right knee up to the chest and then pause. Whilst standing on the left leg, pull the right foot towards the buttock using the right hand. Pause in this position and then step with the right foot and repeat with the left leg.
5. **Walking opposite leg swing** – Take a step with the left leg and swing the right leg towards shoulder height, touching the right foot with the left hand. Keep the leg straight during the swing, and repeat with the opposite limbs. Walk forward for a distance of approximately 10 m.
6. **Arm circles** – Swing arm forward, past the side of the head. Repeat with other arm.

Repeat the above exercises twice (3 times in total).

### Static Stretching

1. Start – 5-minutes of jogging.
2. **Gastrocnemius/Soleus stretch** – Place the hands on the wall and place one foot in-front of the other. Keep the back leg straight to stretch the gastrocnemius. Flex the elbows to increase the stretch. Bend the back leg to stretch the soleus. Hold each stretch for 7-seconds.



3. **Hamstrings stretch** – Sit on the floor with the legs spread-out in-front. Reach down one leg with the hands towards the foot. Hold the stretch for at least 7-seconds. Repeat with the other leg.
4. **Quadriceps stretch** – Stand on the left leg and pull the right foot towards the buttock and hold the stretch for at least 7-seconds. Repeat with other leg.

Repeat the above stretches twice (3 times in total).

### **Sprint Drills**

1. Start – 5-minutes of jogging followed by a series of specific static and dynamics stretches.
2. **High knees** – At jogging pace, move forward lifting alternate knees as high as possible in-front of body. Move arms accordingly. Perform over 10 m.
3. **Heel kicks** – At jogging pace, move forward flicking the heels towards the buttocks. Move arms accordingly. Perform over 10 m.
4. **Stride outs** – Run forward with accentuated stride length. Perform over 10 – 20 m.

Repeat above drills twice each (3 times in total).

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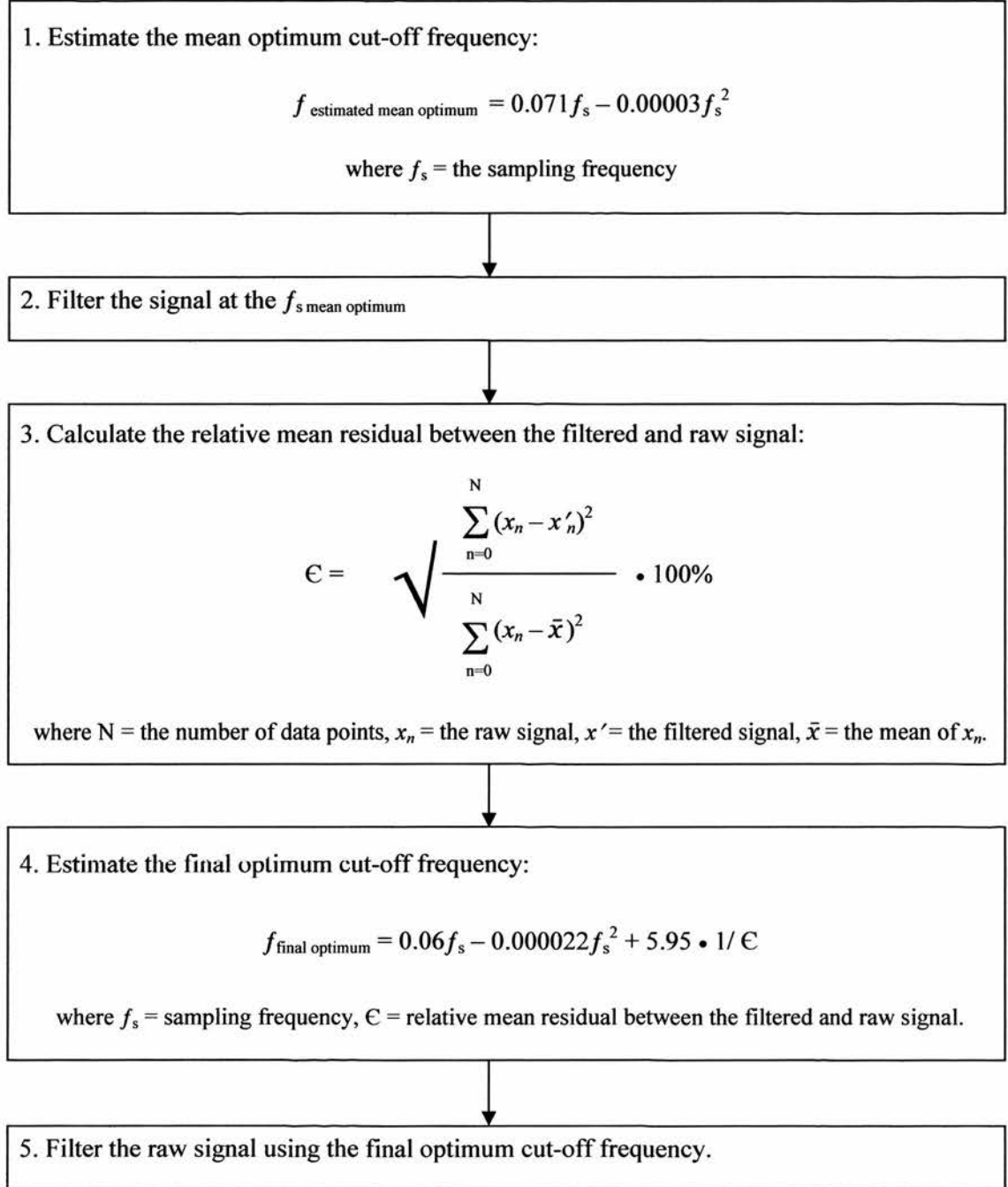
## **APPENDIX A1.4 – SELECTION OF CUT-OFF FREQUENCY FOR THE DIGITAL FILTER**

A second order, dual pass, recursive Butterworth digital filter was used to filter the position data following the digitising procedure. The selection of the cut-off frequency for digital filters has been recommended using the techniques of harmonic and residual analysis (Winter, 1990; Wood, 1982). In harmonic analysis the power of each harmonic component of the signal is examined and a decision is made about the cut-off frequency based upon the power of the signal that should be accepted as useful as opposed to noise (Wood, 1982). Residual analysis involves filtering the data at different cut-off frequencies and determining the appropriate cut-off from the analysis of the residuals between the filtered and raw signal (Winter, 1990). However, both of these techniques have associated problems. For example, when using harmonic analysis there are no objective criteria for selecting the acceptable power within the signal and the technique is based on the assumption that the filter has an infinitely sharp cut-off (Yu et al., 1999). It has been shown that the cut-off frequency determined from residual analysis is only weakly correlated to the sampling frequency which is inappropriate given the relationship of the sampling frequency to the frequency spectrum of the signal (Yu et al., 1999).

Yu et al. (1999) developed a procedure for objectively determining the optimum cut-off frequency for a low-pass Butterworth filter using the sampling frequency and regression models. The protocol involves the steps shown in Figure 1. This procedure estimates a cut-off frequency from the sampling frequency and then an optimum frequency is calculated based upon residual analysis. The authors proposed that this method provided cut-off frequencies that were objective and correlated to the sampling frequency of the movement.

For the present study the selection of a cut-off frequency was ultimately determined from the procedure developed by Yu et al. (1999). However, harmonic analysis was used initially to gain an understanding of the composition of the signals in terms of the frequency location of the majority of the signal. This is important as human movements are at low frequencies whereas random noise occupies the higher end of the frequency spectrum (Winter, 1990). The ankle joint marker (lateral malleolus) was analysed for all participants during the third stride cycle (the fastest stride) from the pre-training testing session. A stride cycle was defined as the period between toe-off and the next ipsilateral toe-off. Toe-off was determined

from the raw data as the point at which the vertical displacement of the 5<sup>th</sup> metatarsal phalangeal joint increased from its position during the stance period of the stride cycle.



**Figure 1** The protocol developed by Yu et al. (1999) for selecting an optimum cut-off frequency for a low-pass Butterworth filter.

The harmonic analysis involved the calculation of the Fourier coefficients for the raw x, y paths of the ankle joint marker using the following formula:

$$A_m = \sum_{r=-n}^{n-1} S_r \cdot \cos \frac{2 \cdot \pi \cdot m \cdot r}{N}$$

and

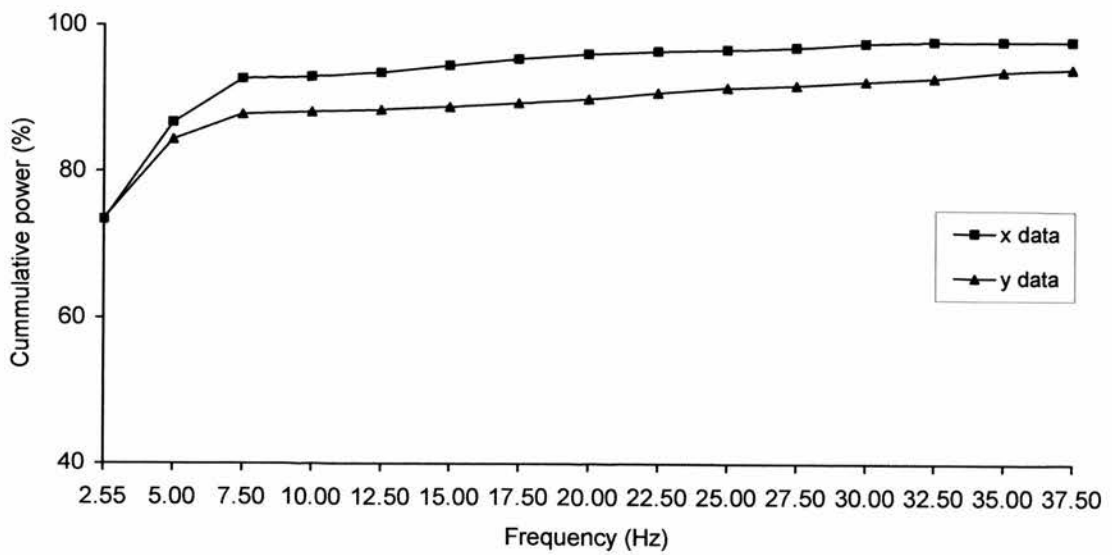
$$B_m = \sum_{r=-n}^{n-1} S_r \cdot \sin \frac{2 \cdot \pi \cdot m \cdot r}{N}$$

where  $A_m$  = amplitude of the cosine function,  $B_m$  = amplitude of the sine function,  $n$  = the number of the data point in sequence,  $S_r$  = the  $r^{\text{th}}$  sample value,  $\pi = 3.1415927$ ,  $m$  = the harmonic number,  $r$  = the number of the sample,  $N$  = the number of data points. The power within each harmonic was calculated using the amplitudes of the Fourier coefficients to produce a power spectrum for each joint:

$$\text{Power within harmonic} = (A_m^2 + B_m^2) \cdot 2$$

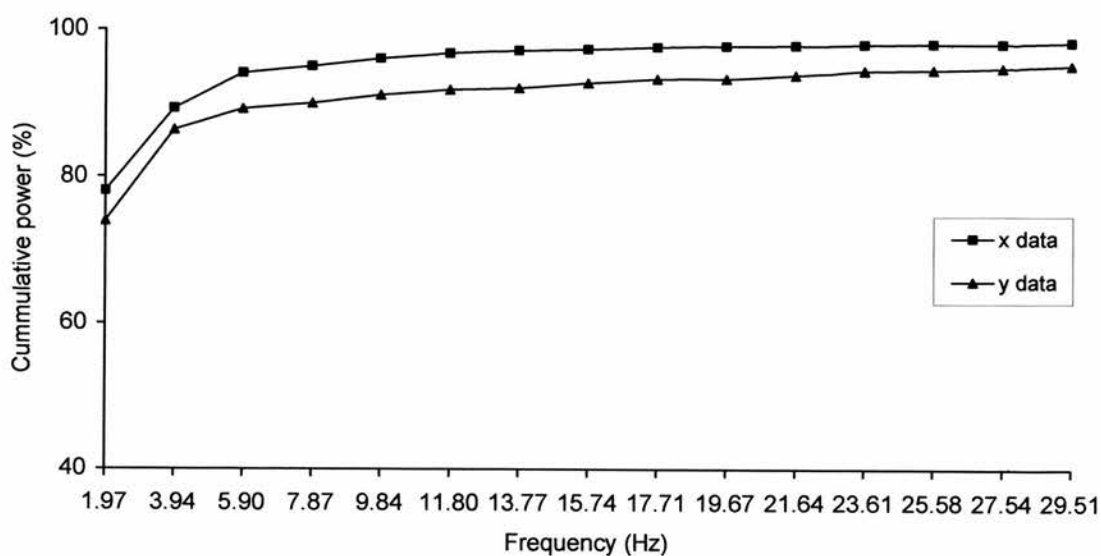
The graph of cumulative power as a function of frequency was viewed for each participant to determine points of inflexion. Examples of such graphs are shown for two participants in Figures 2 and 3. These figures show points of inflexion at 7.50 Hz and 5.90 Hz, respectively. Figures 2 and 3 are typical of the graphs for all participants.

The method of Yu et al. (1999) predicted mean cut-off frequencies of  $8.53 \pm 0.33$  Hz for the x co-ordinates and  $7.94 \pm 0.43$  Hz for the y co-ordinates. As a comparison, harmonic analysis revealed that 90% of the power of the signal was contained within  $6.10 \pm 1.05$  Hz for the x co-ordinates and  $12.58 \pm 7.34$  Hz for the y co-ordinates, while 95% of the power was contained within  $12.53 \pm 4.59$  Hz and  $28.73 \pm 6.02$  Hz for the x and y data, respectively. A cut-off frequency of 7 Hz was selected based on the preceding analysis. This cut-off frequency was applied to all joints during the 3 stride cycles for each participant. This cut-off frequency is in the range of those used by previous authors when analysing joint kinematics during walking (Nissan, 1980) and sprint running during the acceleration phase (Schot & Knutzen, 1992).

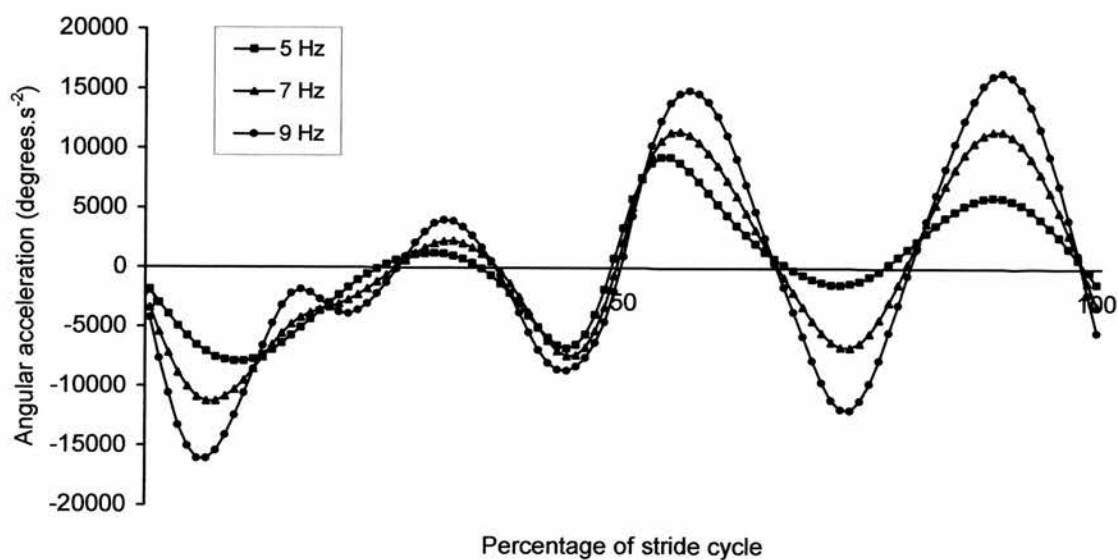


**Figure 2** The cumulative power as a function of frequency for the x, y data of the ankle joint marker for the fastest participant during stride 3 of the 20 m sprint.

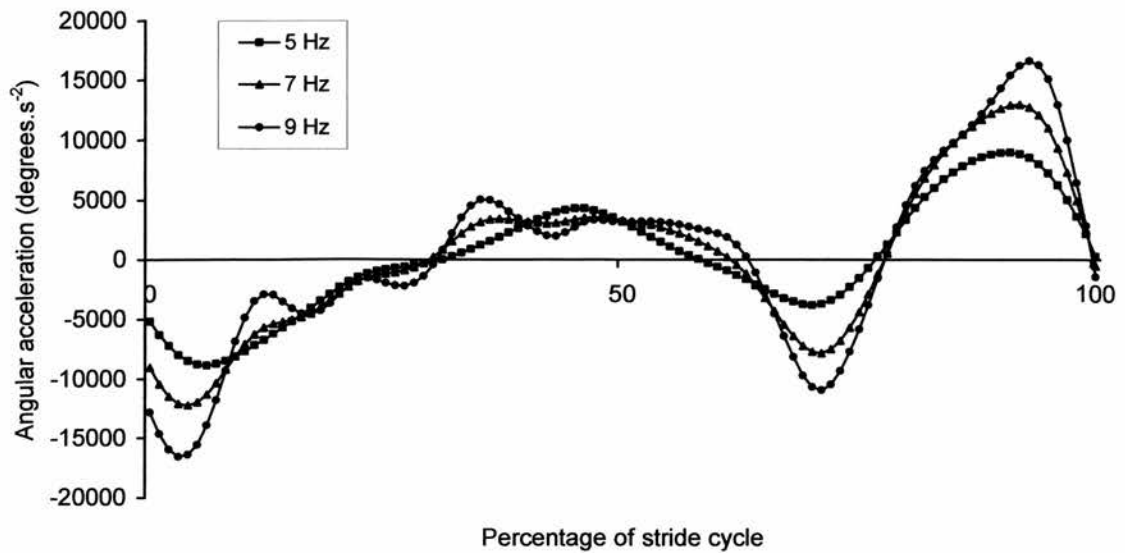
As a comparison of the effects of the different cut-off frequencies, the ankle joint for the fastest and slowest participants during all 3 stride cycles were filtered using cut-off frequencies ranging from 5 Hz up to 9 Hz and the angular acceleration data were graphed. The angular displacement of the ankle joint was calculated using the  $\cos^{-1}$  of the dot product for the foot and shank limb segments. The first and second time derivatives (angular velocity and acceleration, respectively) were then calculated using central finite differences. For each stride at least 15 start and end points were included so that the derivatives of the positional data would not be distorted following the data being filtered (Vaughan, 1982). The data during each stride cycle were then normalised to 101 data points using a quintic spline procedure. Figures 4 and 5 show the acceleration data during the third stride cycle (only graphs for 5 Hz, 7 Hz and 9 Hz are shown, for clarity).



**Figure 3** The cumulative power as a function of frequency for the x, y data of the ankle joint marker for the slowest participant during stride 3 of the 20 m sprint.



**Figure 4** The effects of different cut-off frequencies on the angular acceleration of the ankle joint for the fastest participant during stride 3 of the 20 m sprint.



**Figure 5** The effects of different cut-off frequencies on the angular acceleration of the ankle joint for the slowest participant during stride 3 of the 20 m sprint.

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## APPENDIX A1.5 – CALCULATION OF DIGITISING ERRORS

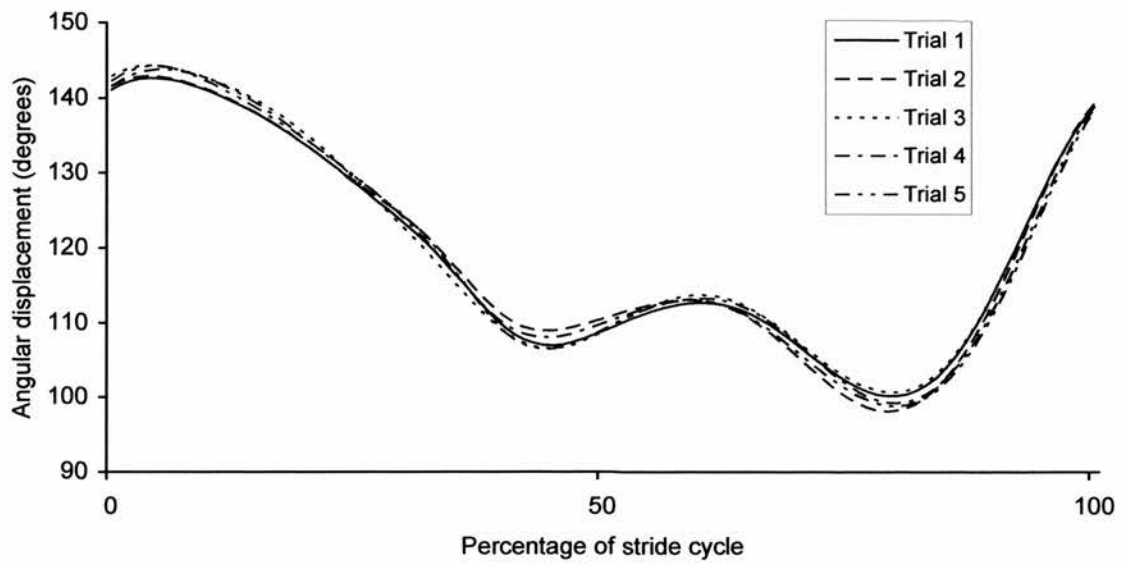
From the data collected during the training study, a trial was selected and digitised manually 5 times in order to calculate the error associated with the digitising process. The trial selected was the fastest achieved by the particular participant during the pre-training testing session. The second stride of the 20 m trial was selected as this was captured by the first camera which covered the greatest area (7.5 m x 3 m) and was therefore deemed prone to greater digitising error.

The second stride cycle was identified using the vertical displacement of the marker on the 5<sup>th</sup> metatarsal phalangeal joint. The data were filtered using a second order, dual pass, recursive Butterworth digital filter with a cut-off frequency of 7 Hz (see Appendix A1.4). Fifteen start and end points were included to avoid distortion following differentiation to calculate the time derivatives of position (Vaughan, 1982). The angular displacement of the joints was calculated using the  $\cos^{-1}$  of the dot product for the foot and shank limb segments. The first and second time derivatives (angular velocity and acceleration, respectively) were calculated using central finite differences for each of the 5 digitised trials. The data for each joint were normalised to 101 data points during the stride cycles using a quintic spline procedure. The angular displacement, velocity and acceleration are shown for the ankle joint in Figures 1, 2 and 3, respectively, for each digitised trial. Continuous relative phase (CRP) was calculated for the shoulder-hip, hip-knee and knee-ankle joint couplings using the techniques described in section 3.44 of the Method.

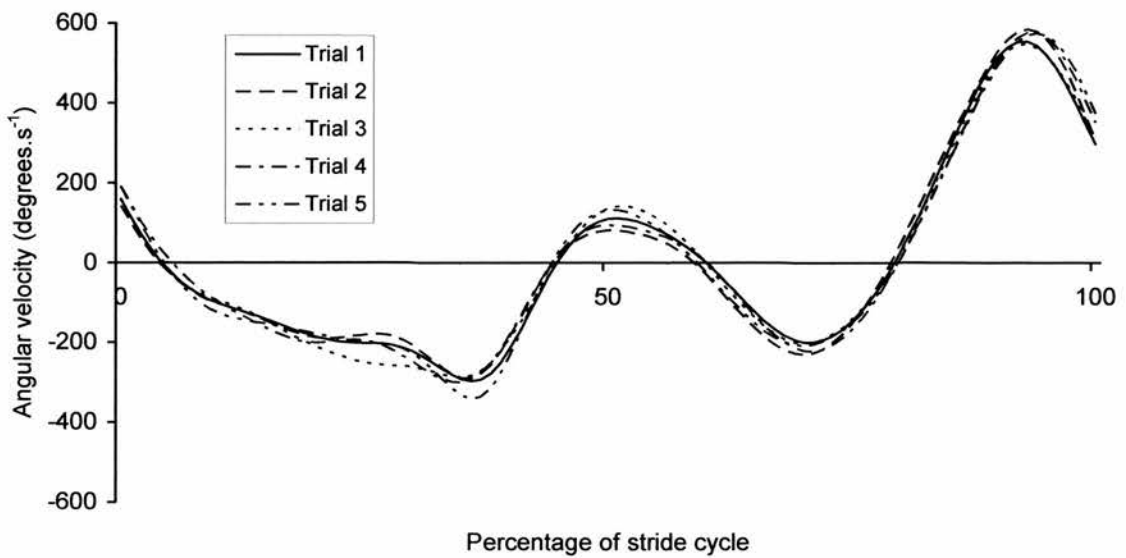
For all of the variables the root mean square error (RMSE) was calculated across each of the 5 digitised trials using the following formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^k \left[ \sum_{j=1}^N (a_{ij} - \chi_i)^2 \right]}{k}}$$

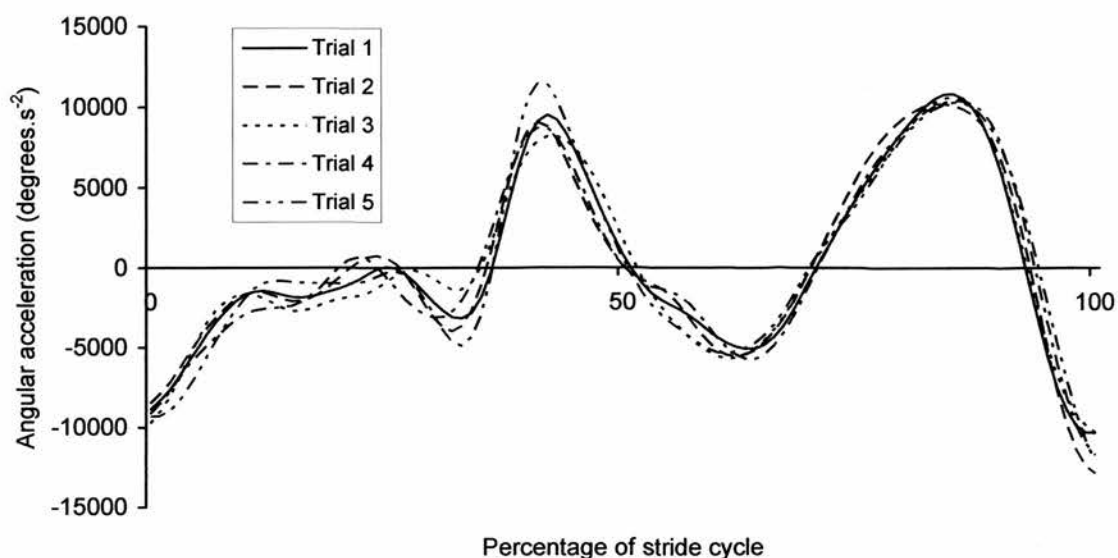
where  $N$  = the number of digitised trials (5),  $a_{ij}$  = the digitised  $i$ th point of the  $j$ th digitised trial,  $\chi_i$  = the mean of the  $i$ th point calculated across 5 digitised trials,  $k$  = the number of data points (101).



**Figure 1** The angular displacement of the ankle joint during stride 2 from 5 repeat-digitised trials.



**Figure 2** The angular velocity of the ankle joint during stride 2 from 5 repeat-digitised trials.



**Figure 3** The angular acceleration of the ankle joint during stride 2 from 5 repeat-digitised trials.

The RMSE calculated from the 5 repeat-digitising trials were compared to the statistics calculated using the data from the pre-training testing session. This allowed the magnitude of the errors produced in the digitising process to be assessed relative to the variation produced in the participant's performance. The methods used to calculate the RMSE for the pre-training data are the same as discussed above, with the mean data from 3 trials calculated for the 17 participants used. Table 1 shows the RMSE data for the joint variables of angular displacement, velocity and acceleration. The CRP data are shown in Table 2.

**Table 1** Root mean square error for the joint kinematic variables calculated across 5 repeat-digitised trials and the mean data from the pre-training testing session. In all cases, stride 2 was analysed.

Kinematic variable	Joint							
	Shoulder		Hip		Knee		Ankle	
	Digitised	Pre-training	Digitised	Pre-training	Digitised	Pre-training	Digitised	Pre-training
Displacement (degrees)	1.01	7.14	0.87	4.24	0.67	4.89	1.64	3.58
Velocity (degrees.s <sup>-1</sup> )	36.47	83.16	22.05	57.88	17.25	82.26	36.69	65.78
Acceleration (degrees.s <sup>-2</sup> )	1234.06	2492.44	933.07	1800.16	710.26	2277.72	1628.83	2549.24

**Table 2** Root mean square error for the continuous relative phase couplings calculated across 5 repeat-digitised trials and the mean data from the pre-training testing session. In all cases, stride 2 was analysed.

	Continuous relative phase coupling		
	Shoulder-hip (degrees)	Hip-knee (degrees)	Knee-ankle (degrees)
	RMSE	RMSE	RMSE
Digitised	4.73	3.04	6.12
Pre-training	11.18	9.91	12.74

Note: RMSE = root mean square error.

The comparisons revealed that the errors produced in the digitising process were less than the variation in the participant’s pre-training performance for all variables calculated, and so digitising error could be rejected as factor causing substantial differences between the pre and post-training data.

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## **APPENDIX A2.1 – THE RELIABILITY OF ACCELERATIVE SPRINT PERFORMANCE: DOES STARTING POSITION MATTER?**

*Journal of Human Movement Studies, 2004, 47, 183-191.*

### **ABSTRACT**

The purpose of this study was to determine the influence of starting position on the reliability of 10 m and 20 m sprint times. Two groups of 11 physically active men attended three separate testing sessions. One group performed three 20 m sprint trials from a standing start position; the other group performed the trials from a crouched start position. Sprint times of 20 m with a 10 m intermediate time were recorded using photocells. Reliability was assessed by calculating intraclass correlation coefficients (ICC) and coefficient of variation (CV) of the mean sprint times recorded at each testing session. No differences were obtained between the testing sessions for any of the sprint times ( $P > 0.05$ ). Both starting conditions produced acceptable reliability for 10 m and 20 m times. The reliability statistics for the sprint times performed from the standing start (ICCs of 0.91, CVs ranging from 1.8% to 1.9%) were similar to those performed from the crouch start (ICCs ranging from 0.87 to 0.90, CVs ranging from 1.5% to 1.6%). In conclusion, the results of this study show that high degrees of test-retest reliability in 20 m sprint performance can be obtained in physically active men regardless of starting position. The results suggest that both standing and crouch starts produce reliable measures of sprinting and either could be used to monitor athletic performance.

## **INTRODUCTION**

In many field sport athletes are required to perform sprints over short distances (Mayhew & Wenger, 1985; Meir, Arthur & Forrest, 1993). As such, short sprint performance tests are often used to monitor athletes or assess the response to a training intervention (Fry et al., 1991; Harman, Garhammer & Pandorf, 2000; Young, Hawken & McDonald, 1996). Despite the widespread use of sprint tests in sport science, there is a paucity of research investigating the reliability of sprint performance. Information on the reliability of such measures is important to determine true changes in performance. Reliability provides an indication of the precision associated with a particular measure and is a vital element in the physiological assessment of athletes. The reliability of a test can be influenced by learning effects (Hopkins, 2000; Hopkins, Schabort & Hawley, 2001) and so familiarisation trials are required where participants practice the test. Moir et al. (2004) reported that familiarisation sessions were not required to obtain an accurate measure of reliability for 10 m and 20 m sprint times in active men.

When performing short sprints there is evidence to suggest that starting block positions can have a significant effect on sprint time (Harland & Steele, 1997), while foot placement during upright starts has also been shown to influence performance (Kraan et al., 2001). If starting position can influence the magnitude of sprint times then there is the possibility that the reliability may also be affected. While coaches may be aware of the effects of starting position on sprint time the influence of starting position on the reliability of the sprint test should also be considered. However, there is no research investigating the effect of different starting positions on the reliability of sprint time. Such information will be valuable for coaches who employ sprint tests to monitor their athletes.

The aim of the present study was therefore to determine the reliability associated with 10 m and 20 m sprint times performed by physically active men from either a standing or crouched start. Reliability for each start condition was calculated across 3 separate sessions using the mean time gained from 3 trials within each session.

## **METHOD**

### **Participants**

Two groups of 11 male physical education students volunteered to participate in the study. Ethical approval was granted by the University of Edinburgh ethics committee and each participant completed an informed consent form in accordance with American College of



Sports Medicine guidelines. The participants were recreationally active, being involved in sports including track and field, soccer and rugby. None of the participants had prior experience of the specific tests used in the study, although sprinting activities were typical across each participant’s sporting background. The physical characteristics of the 2 groups are shown in Table 1.

**Table 1** Physical characteristics of the two participant groups. Values are means  $\pm$  standard deviations.

Group	Age (years)	Mass (kg)	Height (m)
S-S	25.4 $\pm$ 6.5	75.8 $\pm$ 9.5	1.75 $\pm$ 0.06
C-S	25.2 $\pm$ 5.8	75.5 $\pm$ 9.5	1.78 $\pm$ 0.05

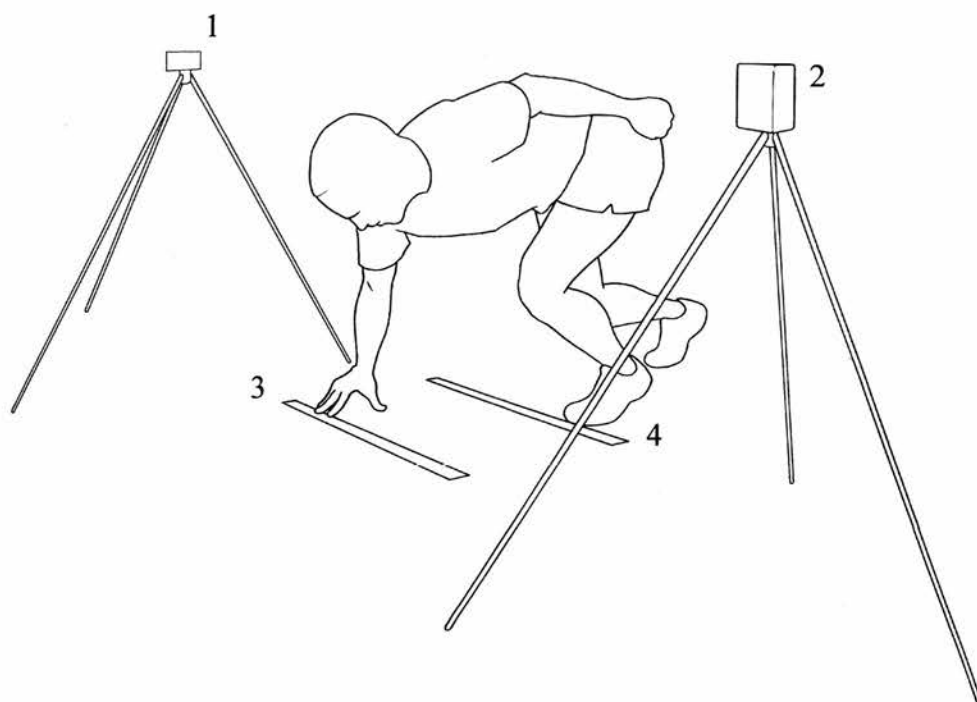
Note: S-S = standing start; C-S = crouch start.

### Study design

This study used a repeated measures design to determine the reliability of accelerative sprint performance from different starting positions. Both groups attended 3 testing sessions on separate days over a 2-week period, with each session separated by a minimum of 72-hours. During each testing session participants completed 3 sprint trials separated by 3-minute rest periods. Participants were asked to maintain their normal diet throughout the testing period and to refrain from strenuous exercise 24-hours before each session. Prior to the tests participants completed a 5-minute warm-up comprising stretches and dynamic exercises. The warm-up remained consistent across all testing sessions.

Sprint performance was assessed in a straight-line, with running times recorded over 10 m and 20 m. All timing was measured using telemetric photocells (Sprint Timer Telemetry, Cranlea & Company, England) placed at the 0, 10 m and 20 m marks of an indoor running track. During the trials all photocells were set at a height of 1m apart from during the crouch start (C-S) in which the first photocells were set at a height of 0.85 m. The participants began each sprint from a line marked 0.5 m behind the start line so as not to break the beam of the first photocells before the sprint was initiated.

For both the standing start (S-S) and the C-S starting positions, participants started with their front foot on the mark 0.5 m behind the start line. However, for the C-S the contralateral hand was placed on the start line (Figure 1). The same start position was ensured for all trials. Each participant performed 3 runs of maximal effort, and the mean of the trials was used in the data analysis.



**Figure 1** The crouch start during the 20 m sprint. Note: 1 = photocell reflector; 2 = transmitter/receiver photocell; 3 = start line; 4 = mark 0.5 m behind start line.

### Statistical analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 11.0, SPSS Inc., Chicago, IL). Measures of central tendency and spread of the data are represented as means and standard deviations (SD). The effect of familiarisation on the mean times from consecutive testing sessions was assessed with a repeated measures analysis of variance (ANOVA) with the level of significance set at  $P < 0.05$ . Any significant inter-session differences were identified with repeated contrasts. Where the contrasts indicated significant between-session differences, the session was removed. Following this, the coefficient of variation (CV) was calculated as a measure of within-individual variation from a two-way ANOVA on the log-transformed raw data, as described by Schabert et al. (1999). Intraclass correlation coefficients (ICC) were calculated from the  $F$  value obtained from the ANOVA using the method described by Bartko (1966). Confidence

limits (95%) for CV and ICC were calculated using the methods outlined by Tate and Klett (1959) and McGraw and Wong (1996), respectively.

### RESULTS

#### Familiarisation

The mean and SD for the 10 m and 20 m sprint times for the 2 different starting positions are shown in Table 2. No significant differences in 10 m or 20 m sprint times were found between any of the 3 sessions for either start condition ( $P > 0.05$ ). Therefore, all 3 testing sessions were used in the subsequent reliability analysis.

**Table 2** Sprint times achieved from the standing start and the crouch start across 3 separate testing sessions. Values are means  $\pm$  standard deviations.

		Session 1	Session 2	Session 3
S-S	10 m	1.83 $\pm$ 0.12	1.82 $\pm$ 0.12	1.83 $\pm$ 0.12
	20 m	3.18 $\pm$ 0.18	3.20 $\pm$ 0.20	3.15 $\pm$ 0.18
C-S	10 m	1.92 $\pm$ 0.10	1.92 $\pm$ 0.10	1.92 $\pm$ 0.08
	20 m	3.31 $\pm$ 0.13	3.28 $\pm$ 0.14	3.29 $\pm$ 0.12

Note: S-S = standing start, C-S = crouch start.

#### Reliability

Table 3 shows the calculated CV and ICC, along with the associated 95% confidence limits for the mean times for the S-S and the C-S. The 10 m and 20 m times from both starting positions demonstrated high test-retest reliability as evidenced by the low within-individual variation (CV range: 1.5% - 1.9%) and high test-retest correlations (ICC range: 0.87 to 0.91).

**Table 3** Coefficients of variation, intraclass correlation coefficients and associated 95% confidence limits for the mean times achieved with the standing start and crouch start over 10 m and 20 m.

	CV (%)	95% confidence limits		ICC	95% confidence limits	
		Lower	Upper		Lower	Upper
S-S 10 m	1.9	1.4	2.7	0.91	0.76	0.97
C-S 10 m	1.6	1.1	2.1	0.90	0.75	0.97
S-S 20 m	1.8	1.3	2.4	0.91	0.77	0.97
C-S 20 m	1.5	1.0	2.0	0.87	0.68	0.96

Note: CV = coefficient of variation, ICC = intraclass correlation coefficient, S-S = standing start, C-S = crouch start.

## DISCUSSION

The results of the present study suggest that high degrees of test-retest reliability in 10 m and 20 m times from either a standing or crouched starting position with physically active men using the mean score of 3 trials can be achieved without the need for familiarisation sessions. The activity status of the participants is likely to have influenced the lack of necessity for any familiarisation sessions. All of the participants participated in sports requiring sprinting and therefore they demonstrated competence in the necessary motor skills required in the present sprint tests because of their involvement in sport, and therefore practice sessions to minimise learning were not required.

The reliability statistics produced under both starting positions in the present study are similar to those reported by Moir et al. (2004) for 10 m and 20 m sprints using the fastest times recorded from a standing start over 5 testing sessions. The slight differences reported between the reliability measures obtained for the different starting positions in the present study were not substantial. Thus, while the starting position used during sprint running might affect the magnitude of the times recorded (Henry, 1952) and the force-time characteristics during the first strides (Kraan et al., 2001), it has little effect on test-retest reliability of 10 m and 20 m sprint times.

The findings of the present study suggest that when monitoring the accelerative sprint performance of physically active males, both standing and crouch starts can produce reliable times, without the need for familiarisation sessions. Coaches who use short sprints to monitor their athletes should be aware that while starting position may affect the magnitude of the sprint time recorded it has little effect on the reliability of the time.

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## **APPENDIX A2.2 – THE INFLUENCE OF FAMILIARISATION ON THE RELIABILITY OF FORCE VARIABLES DURING UNLOADED AND LOADED VERTICAL JUMPS.**

*Journal of Strength and Conditioning Research*, 2005, **19**, 158-163.

### **ABSTRACT**

The purpose of this study was to determine the number of familiarisation sessions required to obtain an accurate measure of reliability associated with force variables recorded during unloaded and loaded (30% and 60% of one repetition maximum squat) static vertical jumps (SJ). Nine physically active men attended 4 separate testing sessions over a 2-week period. Force platform recordings of peak force, peak rate of force development (pRFD), average rate of force development, take-off velocity, average power and peak power were obtained for each jump. During each of the four testing sessions three jumps were performed under each of the load conditions. The average of the force variables were used in the analysis. Familiarisation was assessed using the scores obtained during the 4 separate testing sessions. Reliability was assessed by calculating intraclass correlation coefficients (ICCs) and coefficient of variation (CV) associated with the force variables. No significant differences ( $P > 0.05$ ) were obtained between the testing sessions for any of the force variables. With the exception of pRFD, the force variables showed reasonably good levels of test-retest reliability (ICC range: 0.75 to 0.99; CV range: 1.2% to 7.6%). High levels of reliability can be achieved in a variety of force variables without the need for familiarisation sessions when performing SJ under unloaded conditions and with loads of 30% and 60% of one repetition maximum squat with physically active men.



## INTRODUCTION

Many sporting movements require high force production over a short time period. As such, the assessment of explosive strength is important for evaluating the effectiveness of various athletic training programs. Measures of maximum force, rate of force development and power appear particularly pertinent (Schmidtbleicher, 1992; Siff, 2000; Tidow, 1990) since they are reported as being strongly correlated with measures of athletic performance (Young, 1995; Young, Hawken & McDonald, 1996; Young, McLean & Ardagna, 1995).

Vertical jumps provide a means of monitoring the explosive strength qualities of athletes or assessing the response to various training interventions (Fry et al., 1991; Häkkinen & Komi, 1985a, 1985b; Häkkinen, Komi & Kauhanen, 1986; Harman, Garhammer & Pandorf, 2000; McBride et al., 1999; Viitasalo & Aura, 1984; Young, 1995). The neural and mechanical similarities between vertical jumps and sporting movements such as sprint running has led some authors to highlight the superiority of vertical jumps over isometric tests when evaluating the dynamic capacity of the muscles (Wilson et al, 1995). Moreover, the addition of load during vertical jumps has been shown to provide further insight into the force capabilities of the leg extensor muscles (Bosco et al., 1995; Bosco & Komi, 1979; Bosco et al., 1982; Viitasalo, 1985). For example, the jump height achieved with different loads has been shown to be sensitive to specific training-induced strength changes (Häkkinen & Komi, 1985a, 1985b) and to discriminate between athletes from different disciplines (Driss et al., 2001; McBride et al. 1999). Thus, explosive strength measurements taken under different loading conditions have been encouraged for the assessment of athletes (Tidow, 1990).

Whilst the use of loaded vertical jump performance in the testing of athletes and in research is common, information on the reliability of such measures is sparse. The reliability of performance of a test is concerned with the reproducibility of the performance over multiple trials (Hopkins, 2000). A reliable test is characterised by small within-individual variation and a high test-retest correlation (Hopkins, 2000). Reliability provides an indication of the degree of precision associated with a particular measure and is a vital element in the physiological assessment of athletes.

To provide an accurate assessment of reliability, the effects of learning should be removed to minimise systematic error (Hopkins, 2000; Hopkins, Schabert & Hawley, 2001). Familiarisation sessions allow participants to perform practice trials to ensure performance changes are not the result of learning effects. For example, it has been found that

familiarisation sessions are required for tests of maximum isotonic knee extension strength (Ploutz-Snyder & Giamis, 2001) and various anaerobic cycle ergometry tests (Barfield et al., 2002; Glaister et al., 2003). In contrast, it is reported that familiarisation sessions are not necessary to provide accurate reliability measures for jump height during countermovement and static jumps performed under unloaded and loaded conditions (Arteaga et al., 2000; Moir et al., 2004). However, no research to date has investigated the need for familiarisation and the subsequent reliability of the force variables associated with squat jumps performed with loads of 30% and 60% of one repetition maximum (1-RM). These loads are typical of those that have been used in previous research (McBride et al., 1999; Newton et al., 2002).

The aims of the present study were to determine a) the number of familiarisation sessions required to establish high degrees of test-retest reliability in various force characteristics during unloaded and loaded (30% and 60% 1-RM back squat) static jumps (SJ) in physically active men; and b) the reliability of those same measures once familiarisation had been established.

## **METHOD**

### **Participants**

Nine students volunteered to participate in the study. Ethical approval was granted by the University of Edinburgh ethics committee and each participant completed an informed consent form in accordance with American College of Sports Medicine guidelines. The participants were recreationally active, being involved in sports such as soccer, rugby, track and field and weightlifting. None of the participants had prior experience of the specific tests used in the study, although jumping activities were typical across each participant's sporting background. All participants performed resistance exercises, including squats as part of their training regimes. The mean ( $\pm$  standard deviation) of the participant's age, mass and height, respectively, were:  $25.8 \pm 3.5$  years,  $86.1 \pm 7.4$  kg and  $1.81 \pm 0.05$  m.

### **Study design**

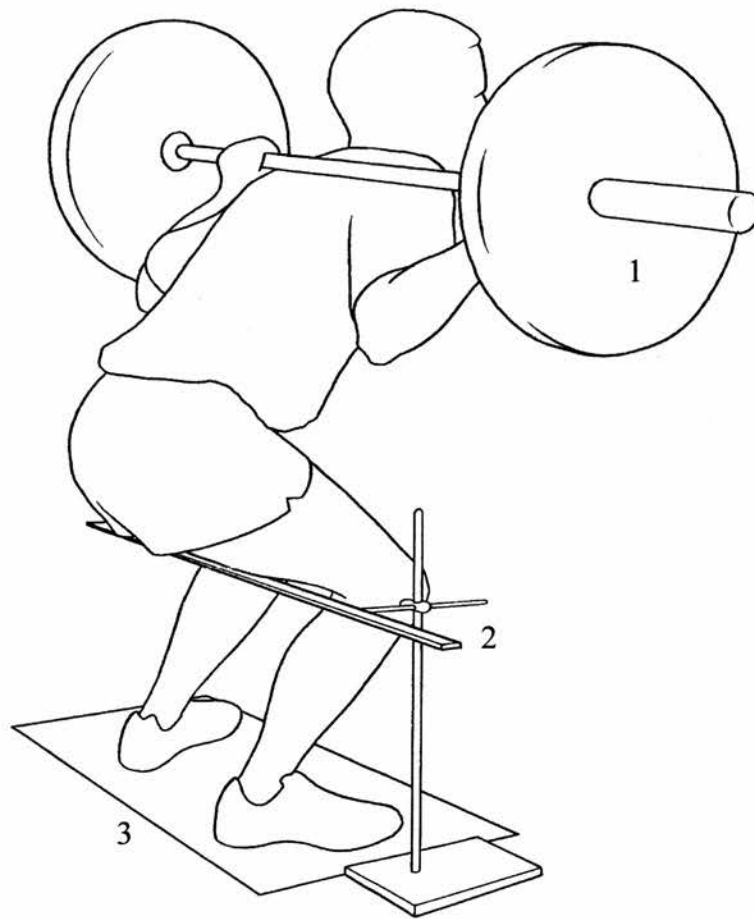
This study used a single-group repeated measures design to determine the number of familiarisation sessions required to provide an accurate measure of the reliability of force characteristics in unloaded and loaded SJ performance in men. All participants attended 4 testing sessions on separate days over a 2-week period with each session separated by a minimum of 48-hours. During each testing session participants completed 3 jumps under 3 different load conditions: unloaded, and with loads of 30% and 60% 1-RM squat. Thus, each

participant completed 9 jumps during each testing session. Participants were asked to maintain their normal diet throughout the testing period and to refrain from strenuous exercise 24-hours before each session. During all testing sessions the unloaded jumps were performed first, followed by the 30% and 60% 1-RM load conditions. Prior to the tests participants completed the same warm-up consisting of 5-minutes of jogging followed by lunging and squatting exercises, including unloaded SJs. No static stretches were performed.

### ***Vertical jump performance***

During each testing session participants performed 3 trials under each load condition with three minutes rest between each jump. Prior to the loaded conditions the participants performed a squat with the barbell to familiarise them with the load. The jumps were performed on a force platform (Kistler, type 9261A, Winterthur, Switzerland) measuring 0.6 m by 0.4 m. Marks were placed on the force platform to ensure that the participant stood in the same place during each testing session. A standard 20 kg Olympic barbell and Olympic disks (Eleiko, Sweden) were used in the 30% and 60% 1-RM conditions.

The SJ required the participant to descend to a knee angle of 90° that was indicated by an adjustable bar that touched the back of the participant's thighs when the correct depth was achieved (Figure 1). The correct knee angle was ensured by using a goniometer. The exact position of the adjustable bar adjacent to the force platforms was maintained to ensure that the depth of each participant's descent was consistent across the testing sessions. The 90° knee angle squat position was held for approximately 3-seconds, as indicated by the tester, following which the participant jumped for maximum height without a prior countermovement. The force recording was initiated prior to each jump and 3-seconds of data were recorded. The analogue signal from the force plate was amplified by charge amplifiers (Kistler, type 5001, Winterthur, Switzerland). Data were sampled at 250 Hz and the analogue signal was converted to a digital signal using Pro-Vec software. In the unloaded jumps the participant's hands were placed on their neck to avoid assistance during the movement. Spotters were employed during the loaded jump conditions. All of the jumps were performed under the guidance of the same tester in all 4 testing sessions.



**Figure 1** Experimental set-up for the loaded vertical jump protocols. The participant picks up the loaded barbell and then steps onto the force platform. The participant then descends until the back of the thighs touch an adjustable bar. This position is held for approximately 3-seconds before the participant jumps for maximum height. Note: 1 = loaded barbell; 2 = adjustable bar set to each participant's 90° knee angle; 3 = force platform.

Prior to the calculation of the force variables, the vertical force-time traces were filtered using a fourth order Butterworth low-pass filter. Using the methods described by Yu et al. (1999) a cut-off frequency of 17 Hz was selected for the unloaded jumps while the loaded jumps were filtered at 18 Hz. These cut-off frequencies are similar to those used previously to filter force data from vertical jumps (Rahmani et al., 2001). The mean of each force variable calculated across the 3 jump trials performed under each load condition during each testing session were used in the subsequent statistical analysis.

### ***Calculation of force variables***

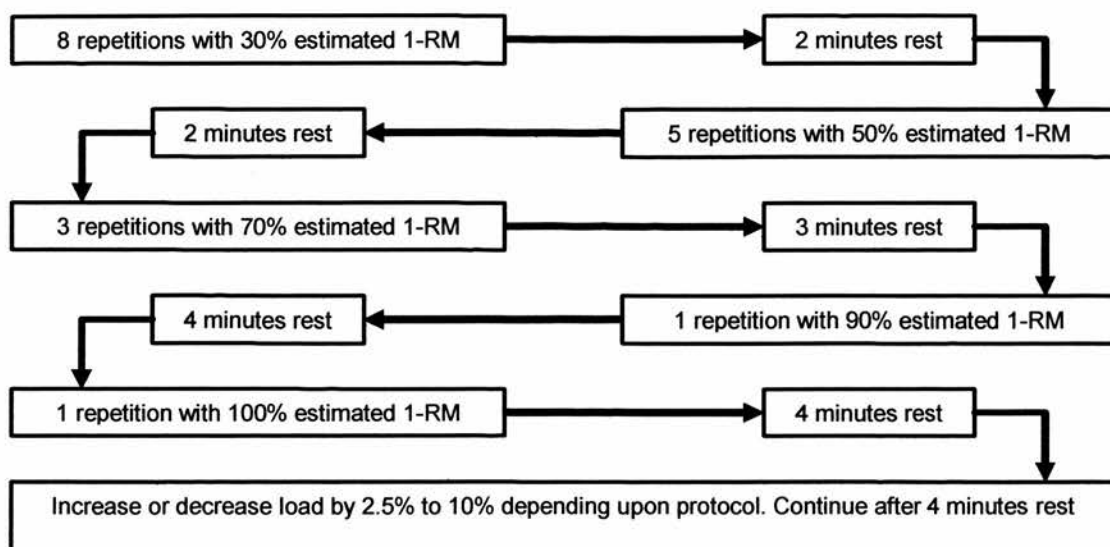
The force variables of peak force (PF), peak rate of force development (pRFD), average rate of force development (aRFD), take off velocity (TO), average power (AP) and peak power (PP) were calculated from the vertical force-time trace during each jump. A jump was deemed to have started when the vertical force exceeded 10 N greater than the mass of the participant or the mass of the participant and the loaded barbell during the held squat position. The initial mass of the participant or mass of the participant and the loaded barbell was taken as the mean vertical ground reaction force over a 0.20 second period (44 samples) during the held crouch position prior to the initiation of the jump.

PF was calculated as the maximum force achieved over the force-time trace during the jump. pRFD was calculated as the maximum value that occurred over the first derivative of the force-time trace. The first derivative was calculated using the finite central difference method. aRFD was calculated as the peak force divided by the time taken to achieve the peak force. TO was calculated by integrating the force-time trace using the trapezoid rule where TO is considered equal to the impulse divided by the mass of the participant or the mass of the participant and the additional load.

The instantaneous velocity trace that was calculated from the integration of the force-time trace was used in the calculation of average and peak power. Specifically, the instantaneous vertical force was multiplied by the instantaneous velocity throughout the propulsive phase of the jump, yielding instantaneous power. The maximum value was taken as PP as previously used with vertical jumps (Harman et al., 1990). The instantaneous power trace was further integrated to provide the work during the propulsive phase of the jump. The total work during propulsion was then divided by the time of the propulsion phase to provide a measure of AP.

### ***1-RM parallel squat protocol***

A 1-RM parallel back squat was performed by each participant prior to the vertical jump sessions in order to calculate the loads to be used. The participants were required to descend to a depth where the top of the thighs were parallel to the floor. The 1-RM testing protocol was based upon that proposed by Baechle, Earle and Wathen (2000). Briefly, each participant's maximum load was estimated between 1.2 and 1.8 times body mass or taken as advised by the participant. The participant then performed parallel squats using the increments shown in Figure 2.



**Figure 2** The repetitions, loads and rest periods used to obtain one repetition maximum parallel squat load.

Following the estimated 1-RM attempt the load was increased or decreased in 5% increments depending upon whether the participant's lift was successful or otherwise. Spotters were used during the squat attempts. A minimum of 48-hours separated the 1-RM squat session from the first vertical jump session.

### Statistical analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS for Windows, version 11.0, SPSS Inc., Chicago, IL). Measures of central tendency and spread of the data were represented by means and standard deviations (SD). The effect of familiarisation on the mean force variables recorded during consecutive testing sessions was assessed with a repeated measures analysis of variance (ANOVA) with the level of significance set at  $P < 0.05$ . Any significant inter-session differences were identified using repeated contrasts. Where significant between-session differences occurred, the initial session was removed. Following the above, the coefficient of variation (CV) was calculated as a measure of within-individual variation from a two-way ANOVA on the log-transformed raw data as described by Schabort et al. (1999). The dependent variables in the ANOVA model were the force variables, with session number as a fixed effect and participant identity as a random effect. CV was determined from the residual error of the ANOVA. By using this procedure, changes in the mean between testing sessions are not added to the coefficient of

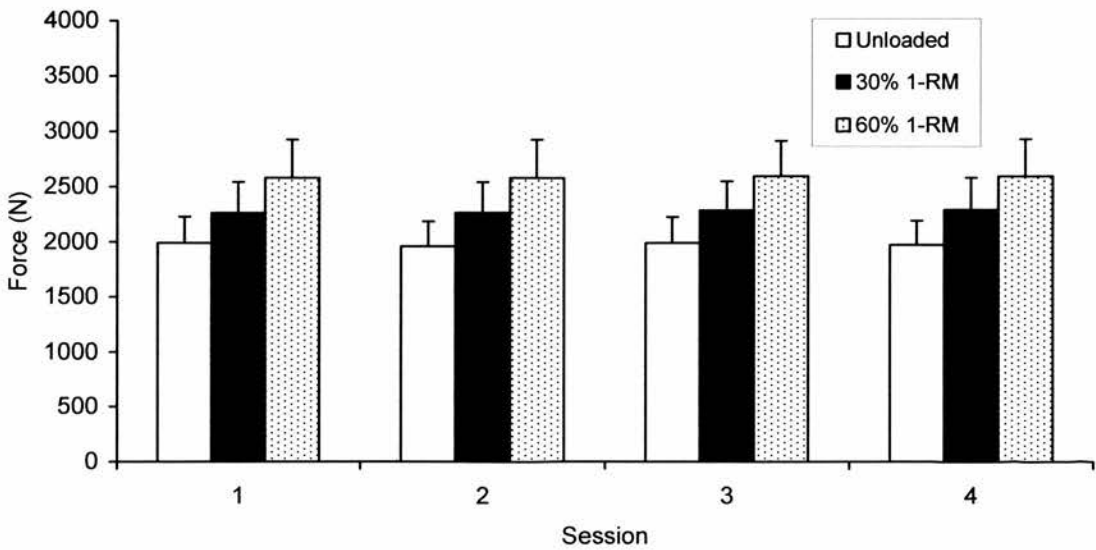
variation (Hopkins, 2000). Intraclass correlation coefficients (ICC) were calculated from the F value obtained from the ANOVA using the method described by Bartko (1966). Confidence limits (95%) for CV and ICC were calculated using the methods outlined by Tate and Klett (1959) and McGraw and Wong (1996), respectively.

### RESULTS

The 1-RM protocol established individual 1-RM loads in  $4.4 (\pm 1.1)$  lifts. Mean parallel squat 1-RM was  $145.8 \pm 33.3$  kg. Mean loads during the 30% and 60% 1-RM conditions were  $44.0 \pm 10.5$  kg and  $87.2 \pm 20.2$  kg, respectively.

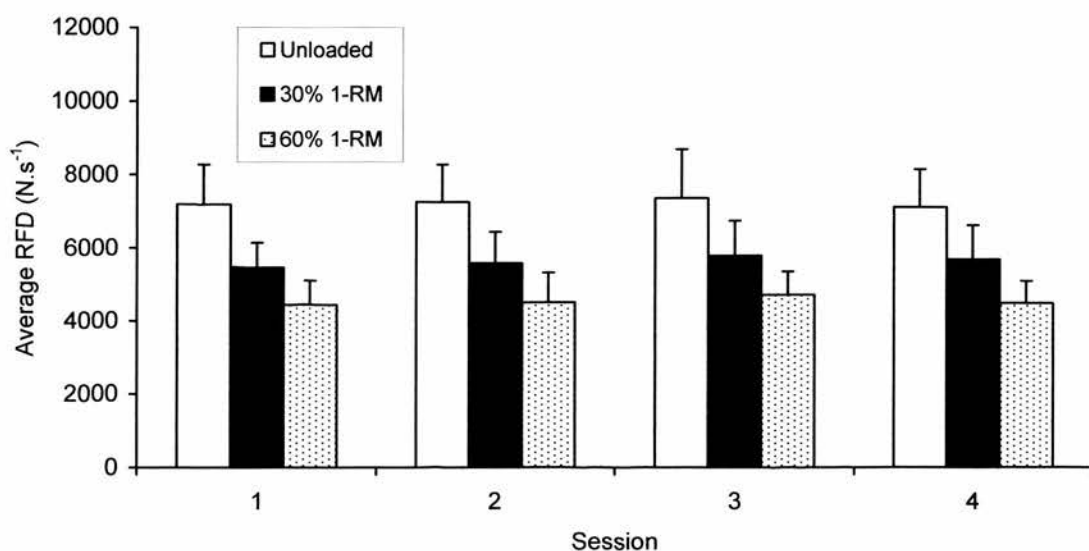
#### Familiarisation

The mean values for PF, aRFD, TO and AP recorded across the 4 separate testing sessions are shown in Figures 3 to 6 as examples of the force-time characteristics. No significant differences were found between any of the sessions for any of the force characteristics during the 3 different load conditions ( $P > 0.05$ ). Therefore, the data from all 4 testing sessions were included in the subsequent reliability analysis.

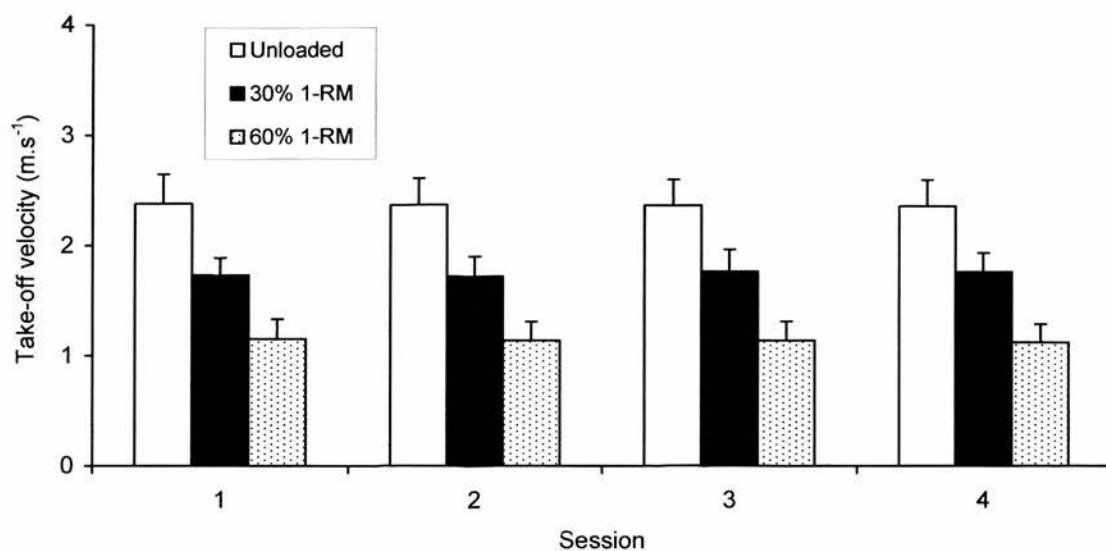


**Figure 3** Peak force achieved during unloaded and loaded static vertical jumps across 4 separate testing sessions. Values are means; bars are standard deviations.

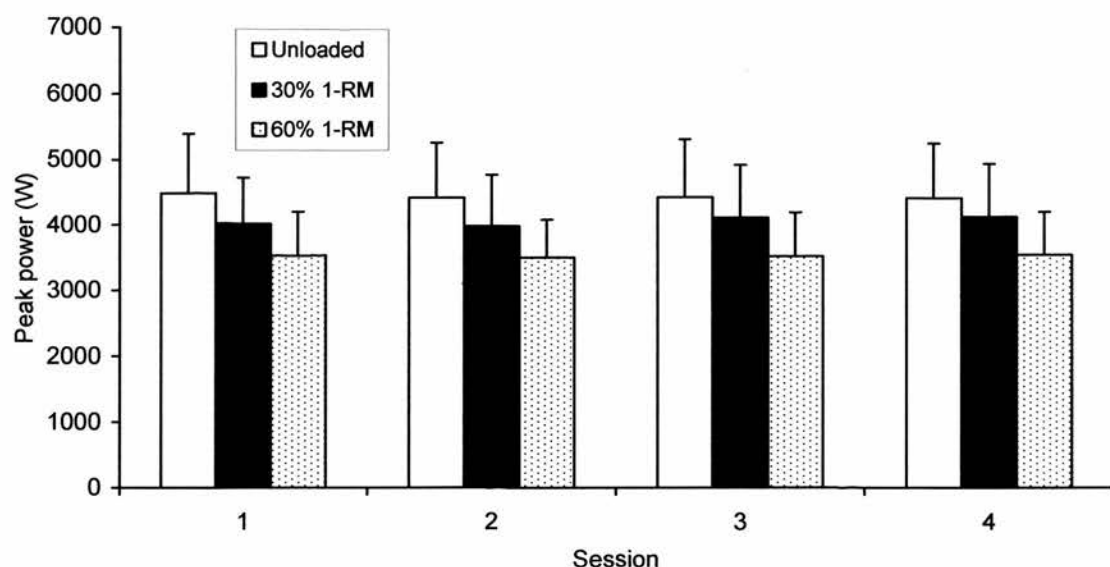




**Figure 4** Average rate of force development achieved during unloaded and loaded static vertical jumps across 4 separate testing sessions. Values are means; bars are standard deviations.



**Figure 5** Take-off velocity achieved during unloaded and loaded static vertical jumps across 4 separate testing sessions. Values are means; bars are standard deviations.



**Figure 6** Peak power achieved during unloaded and loaded static vertical jumps across 4 separate testing sessions. Values are means; bars are standard deviations.

### Reliability

Table 1 shows the calculated CV and ICC, along with the associated 95% confidence limits for each of the variables recorded during the unloaded jump condition. The corresponding values for the 30% and 60% 1-RM load conditions are shown in Tables 2 and 3, respectively. With the exception of pRFD, all force variables demonstrated high test-retest reliability as evidenced by the low within-individual variation (CV range: 1.2 % - 7.6%) and high test-retest correlations (ICC range: 0.75 - 0.99).

**Table 1** Coefficients of variation, intraclass correlation coefficients and associated 95% confidence limits for the force-time variables during unloaded static jumps.

Force variable	CV (%)	95% CL	ICC	95% CL
PF	2.4	1.8 – 3.2	0.96	0.89 – 0.99
pRFD	12.7	9.3 – 16.9	0.53	0.20 – 0.84
aRFD	6.5	4.8 – 8.7	0.84	0.64 – 0.96
TO	2.8	2.0 – 3.7	0.93	0.83 – 0.98
AP	4.6	3.3 – 6.2	0.94	0.84 – 0.99
PP	3.3	2.4 – 4.5	0.97	0.92 – 0.99

Note: CV = coefficient of variation; ICC = intraclass correlation coefficient; CL = confidence limits; PF = peak force; pRFD = peak rate of force development; aRFD = average rate of force development; TO = take off velocity; AP = average power; PP = peak power.

**Table 2** Coefficients of variation, intraclass correlation coefficients and associated 95% confidence limits for the force-time variables during 30% 1-RM loaded static jumps.

Force variable	CV (%)	95% CL	ICC	95% CL
PF	1.5	1.1 – 2.1	0.98	0.96 – 1.00
pRFD	14.1	10.4 – 18.8	0.56	0.23 – 0.85
aRFD	4.6	3.4 – 6.2	0.91	0.78 – 0.98
TO	4.6	3.4 – 6.2	0.81	0.59 – 0.95
AP	4.7	3.4 – 6.4	0.94	0.84 – 0.99
PP	3.0	2.2 – 4.1	0.98	0.93 – 0.99

Note: CV = coefficient of variation; ICC = intraclass correlation coefficient; CL = confidence limits; PF = peak force; pRFD = peak rate of force development; aRFD = average rate of force development; TO = take off velocity; AP = average power; PP = peak power.

**Table 3** Coefficients of variation, intraclass correlation coefficients and associated 95% confidence limits for the force-time variables during 60% 1-RM loaded static jumps.

Force variable	CV (%)	95% CL	ICC	95% CL
PF	1.2	0.9 – 1.6	0.99	0.98 – 1.00
pRFD	17.1	12.6 – 22.9	0.84	0.64 – 0.96
aRFD	7.6	5.6 – 10.1	0.75	0.48 – 0.93
TO	6.4	4.7 – 8.5	0.84	0.64 – 0.96
AP	6.9	4.9 – 9.4	0.87	0.67 – 0.97
PP	4.2	3.0 – 5.8	0.94	0.84 – 0.99

Note: CV = coefficient of variation; ICC = intraclass correlation coefficient; CL = confidence limits; PF = peak force; pRFD = peak rate of force development; aRFD = average rate of force development; TO = take off velocity; AP = average power; PP = peak power.

# DISCUSSION

The first aim of the present study was to determine the number of familiarisation trials required to obtain high degrees of reliability in force variables recorded during unloaded and loaded static vertical jumps. The results of the present study indicate that high degrees of test-retest reliability in force measures with physically active men are achieved without the need for familiarisation sessions.

Moir et al. (2004) reported that familiarisation sessions were not required for loaded (10 kg) and unloaded SJs in physically active men. The authors suggested that the lack of necessity for familiarisation sessions was influenced by the activity status of the participants and the nature of the tests. The same explanation is proposed for the present findings with the participants demonstrating competence in the necessary motor skills required in the jump

tests because of their involvement in sport. Similarly, all participants performed squats as part of their resistance training regimes. A lack of sufficient experience with the movements associated with the tests could account for the requirement of at least one familiarisation session in previous research investigating maximum knee extension strength (Ploutz-Snyder & Giamis, 2001) and peak power output during cycle ergometry tests (Barfield et al., 2002; Glaister et al., 2003). These findings highlight the importance of carefully selecting the correct mode of assessment when comparing the strength and power of athletes from different athletic disciplines. However, the results of the present study combined with those of previous research (Arteaga et al., 2000; Moir et al., 2004) suggest that the similarity between vertical jumps and a variety of sporting movements makes the vertical jump a valuable assessment measure that does not require familiarisation.

With the exception of pRFD the results of the present study support a high degree of reliability for force variables recorded during static jumps using no load and loads of 30% and 60% 1-RM (Tables 1, 2 & 3). The poor reliability of pRFD has implications for those studies that have used this measure to assess performance (Haff et al., 1997). Based on the present findings aRFD may provide a more reliable measure of explosive performance.

The CVs associated with the force variables of aRFD, TO, AP and PP tended to increase as the load used during the SJs increased (Tables 1, 2 & 3). Some research has used loads as high as 90% 1-RM to assess force and power capabilities during vertical jumps (McBride et al., 1999). It is possible that under such high loads some force-time variables may become less reliable and caution may be required when interpreting possible changes in such variables as a result of experimental interventions. However, future research is required to substantiate this claim.

The present study appears to be the first to assess the reliability of force variables recorded during unloaded and loaded vertical jumps using physically active men. Despite the high degree of reliability demonstrated in the present study, it should be noted that some authors have reported differences in reliability of power output measures between males and females (Hopkins, 2000). Therefore, future research should investigate the reliability of force measures in female athletes.

Loaded and unloaded vertical jumps provide a valuable means of evaluating the effectiveness of various athletic training programmes. The results of the present study

suggest that the assessment of a number of force variables from the average of 3 attempts during this type of activity provide high degrees of test-retest reliability in physically active men. Furthermore, this reliability can be achieved without the need to perform familiarisation sessions, supporting the suitability of the tests for monitoring athletes (e.g. Young, 1995) and assessing the effects of various experimental interventions (e.g. Newton et al., 2002). Researchers and practitioners should be aware of possible problems when using the pRFD calculated from the ground reaction force measured on a force platform. Although this measure can be considered an informative variable as to the force capabilities of the active musculature, the reliability is questionable. Calculating the aRFD provides a more reliable measure, and one that is equally informative. However, the findings of the present study may not extend to the reliability of the tests for female athletes.

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